# Time Traveling: Forgotten Great Chronometric Expeditions to Map Earth

By: **Trudy E. Bell** ©2020 Trudy E. Bell

Before the telegraph, astronomers worldwide discovered that accurate marine chronometers could be used to map differences in longitudes on land.

The Royal Observatory operation between Greenwich, England, and Valentia, Ireland, in late June 1844 was as elaborate and as precise as a gold heist:

> A great number of strong boxes were constructed, all exactly similar, and of such dimensions that the large flat cases could be thrust easily into any one of them (one flat case upon the other), and could there be held firmly… The strong boxes were all furnished with similar locks, which could all be opened by the same key. One of these strong boxes was attached by powerful screws to every one of the railway-carriages, steam-boats, and mail-coaches… At each of the stations where the course of any railway-carriage, steam-boat, mail-coach, or car, began or ended, an agent was stationed, who was furnished with a key which would open any of the locks. …At the beginning of each section of the line an agent conveyed the flat cases to the carriage or steam-boat, placed them in the strong box, and locked it…at the end of that section another agent unlocked the strong box and took the flat cases out of it.[1]

The two flat cases rode by rail from Greenwich to Liverpool, where they were transferred to a strong box in a mail steamboat to Kingstown. They traveled by rail from Kingstown to Dublin, then atop horse-drawn mail coaches through Limerick and Tralee more than 200 miles across Ireland to Cahersiveen. The cases then were laid in the bottom of a Coast Guard boat, which ferried them across a narrow sound to the island of Valentia (also spelled Valencia), westernmost point of all Europe.

By then, it was midnight. But the hardest work of the mission still lay ahead: more than three miles of trekking on foot in darkness, climbing 900 feet over slippery grass and rugged rock—the large strong box "carried by two men, by means of two poles fixed in staples, in the manner of a sedan-chair." Their destination: the remote summit of Feagh Main, the highest point on Valentia, atop which had been built a "paneled hut covered with canvas."[1]

That humble hut was a temporary astronomical observatory, housing a transit telescope swung between two stone piers, plus several observatory clocks. No rest for the weary: right away, after the arduous journey of 620 miles, the strong box was unlocked. The two flat cases were slid out of it and opened, revealing their treasure: nestled in individual padded compartments lay 30 gleaming pocket chronometers.

**Linking Time with Longitude**

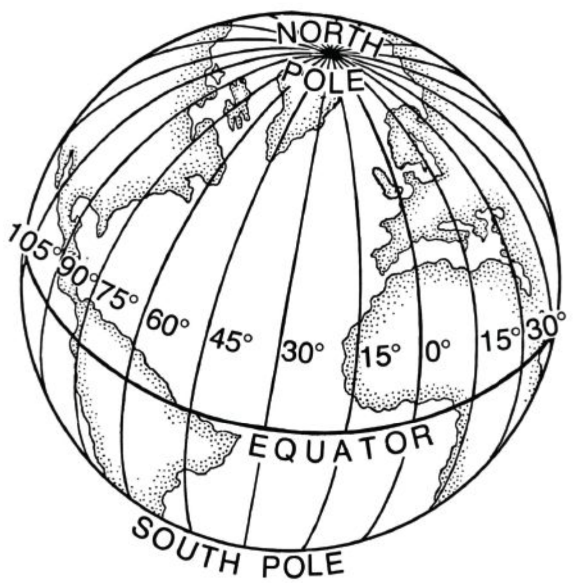
Dava Sobel's 1995 bestselling book *Longitude* described how beginning in 1714 the British Board of Longitude offered princely awards for any device or technique that could reliably ascertain longitude at sea. Prizes ranged up to £20,000—equivalent to about £2.5 million today—for nailing longitude to within half a degree (i.e., to within about 27 miles at 40 degrees latitude). Over decades, John Harrison submitted five different prototypes he built of chronometers—the most accurate clocks built up to then; by the 1770s, he ultimately received a series of payments approximately equal to the prize.

The principle behind using a chronometer to determine longitude is this: longitude bears a fixed relationship to time. Anywhere on Earth at local solar noon, the sun is directly on the meridian—the imaginary line running due north-south through that location's zenith. If one such location is defined as 0 degrees longitude, then it can serve as Earth's "prime meridian"— the reference longitude from which every other location on Earth can be determined.

*Box marine chronometer, shown face-down to display the mechanism, was made by Charles Frodsham of London between 1844-60. Parkinson & Frodsham chronometers were among the 92 chronometers used in the U.S. Coast Survey transatlantic chronometric expeditions (1849, 1850, and 1851), which sought to precisely measure the difference in longitude between the Royal Observatory, Greenwich, and the Harvard College Observatory. This chronometer, from the Ladd Observatory collection at Brown University, was later modified by Wm. Bond & Son of Boston to be used with the telegraph). Credit: Wikimedia Commons*

The Royal Observatory at Greenwich was established as the UK prime meridian in 1721, but Paris in France, Berlin in Germany, Cadiz in Spain, and cities in other countries established their own prime meridians. Given the vastness of the Atlantic Ocean, there was also serious debate whether there should be an American prime meridian.

A marine chronometer needed to be accurate and precise enough to serve as a portable time standard, keeping Greenwich time (or the time of any other desired meridian) in the midst of the trackless ocean during a voyage. Each midday, a sailor with a sextant determined the moment of the ship's local noon (i.e., sun on the meridian); then, he immediately checked the ship's chronometer to determine the time on the prime meridian, and from the difference calculated the ship's longitude at sea. The best chronometers had an error in their rates corresponding to a longitude error of several to many miles over a month-long voyage.




*Because there are 24 hours in a solar day and 360 degrees of longitude around the globe, every hour of time corresponds to 15 degrees of longitude. Conversely, every degree of longitude is equivalent to 4 minutes of time. However, because meridians of longitude converge at the poles, the physical distance represented by a degree of longitude varies with latitude, exceeding 69 miles at the equator but spanning only 53 miles at 40 degrees north or south latitude, and even less closer to the poles. Credit: Pearson Scott Foresman/Public Domain*

**Chronometric Technology Race**

Harrison's triumph, although the end of Sobel's book, was not the end of the story. In fact, his invention triggered a chronometric technology race.

You'd think that every shipping company would have immediately jumped on reproducing and fielding Harrison's invention. But for a good quarter-century, hardly any chronometers were built or used in commercial shipping. Among other reasons, the invention needed significant improvements, including the ability to keep accurate time despite daily changes in ambient temperature. The devices were also extremely expensive, the equivalent of half a year's pay for an average day laborer. Moreover, the late 1700s and early 1800s were decades before the standardization of the inch and other units of measurement enabled interchangeable parts and mass production of faithful replicas.

Nonetheless, the British Empire built its might on seafaring, and the Admiralty sought the best chronometers for military navigation. So, scores of clockmakers around major British—and European, and later American—ports and cities began inventing and manufacturing their own chronometers, striving for designs ever more compact and ever more accurate and reliable. In 1805, the Admiralty ruled that before chronometers could be sold, they needed to pass exacting official tests.

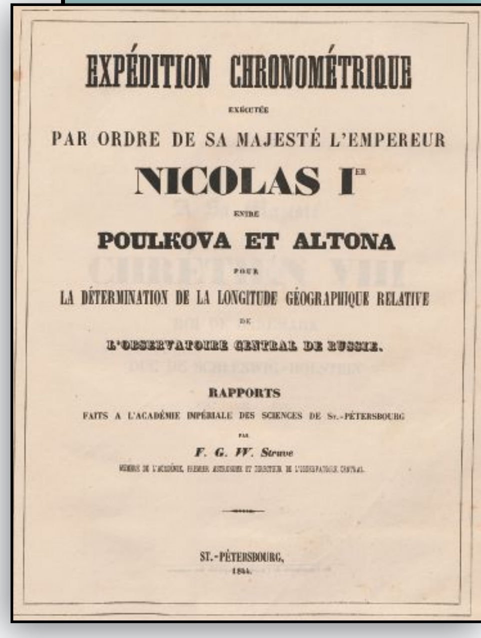
Moreover, in the 1820s—decades before the telegraph brought virtually instantaneous point-to-point communication, and the spread of railroads compelled the adoption of regional time zones—it became clear to a number of astronomers and cartographers that a vision first articulated centuries earlier was at last within reach: good marine timekeepers could be used to determine longitudes *of fixed locations on land* as well as transient locations of ships at sea.

**The Mapping Conundrum**

It is difficult now—in the 21st century when satellite mapping, instantaneous international communications, and GPS accurate to feet are at everyone's fingertips—to grasp just how unmapped the Earth was two centuries ago. Although many nations surveyed borders and triangulated key landmarks in their interiors to produce charts and to inventory natural resources, meshing local, regional, and national maps together was a challenge.

Problem was, various astronomical methods of determining differences in longitude gave inconsistent results. Several key methods involved the moon—but the moon's motion (which is mathematically complex, as it feels the gravitational pull not only of Earth but also of the sun) was only imperfectly known. As a result, in the early 19th century, where different maps met, meridians of longitude sometimes differed from one another by a mile or more.

Enter the chronometer. In 1821, Danish-German astronomer Heinrich Christian Schumacher (founding editor of the major international astronomical journal *Astronomische Nachrichten*, still published today) used chronometers to determine the difference in longitude between two points nearly 200 miles apart (Copenhagen, Denmark, and Hamburg, Germany) within a second of time, corresponding to a longitude error of maybe 100 feet.


EXPÉDITION CHRONOMÉTRIQUE

EXÉCUTÉE

PAR ORDRE DE SA MAJESTÉ L'EMPEREUR

NICOLAS Ier

ENTRE

POULKOVA ET ALTONA

POUR

LA DÉTERMINATION DE LA LONGITUDE GÉOGRAPHIQUE RELATIVE

DE

L'OBSERVATOIRE CENTRAL DE RUSSIE.

RAPPORTS

FAITS A L'ACADÉMIE IMPÉRIALE DES SCIENCES DE ST.-PÉTERSBOURG

[illegible]

F. G. W. Struve

MEMBRE DE L'ACADÉMIE, PREMIER ASTRONOME ET DIRECTEUR DE L'OBSERVATOIRE CENTRAL.

ST.-PÉTERSBOURG,

1844.

*Title page of the report on the major chronometric expedition run by Wilhelm Struve, director of the Pulkovo Observatory in Russia (near present-day St. Petersburg, and then the observatory with the largest telescope in the world), published in 1844. It was the first of two major expeditions Pulkovo ran in the 1840s to determine the longitude of Pulkovo with respect to Altona and Greenwich. Credit: ETH-Bibliothek Zürich/Public Domain Mark*

In 1822 and 1823, by order of the Board of Longitude, British astronomer John Lewis Tiarks (who had just surveyed the U.S.–Canadian boundary) conducted the first chronometric expeditions between Falmouth, Dover, and the island of Madeira (southwest of Portugal some 1,350 miles away) on behalf of the Admiralty. He compared the resulting chronometric longitudes to those determined by the Trigonometrical Survey of the Board of Ordnance—a precision triangulation of angles and distances among 300 key landmarks across Great Britain (including Ireland and Wales) that had been underway since 1791.

To Tiarks's dismay, both of his chronometric expeditions revealed that the longitude differences across Britain measured by the Trigonometrical Survey were proportionately (depending on distances between points) up to three seconds of time (i.e., up to some 250 feet) too small. Given the Survey's then-unprecedented nominal precision of *hundredths* of a second of time (i.e., less than a foot), Tiarks suspected that the discrepancies arose from variations in the shape of the Earth away from a perfect oblate spheroid over long distances.

### Earth's Figure

Schumacher's and Tiarks's findings inspired several major national and international chronometric expeditions over the next two decades, each more ambitious than the last. It was during this heyday, in summer 1844, that Astronomer Royal George Biddle Airy—director of the Royal Observatory, Greenwich—extended the network of longitudes to the westernmost point of Europe with the elaborate chronometric expedition between Greenwich and Valentia. The 30 borrowed pocket chronometers in the two flat boxes traveled by rail, boat, carriage, and foot back and forth nine times, traveling more than 10,000 miles. The Valentia expedition revealed that the difference in longitude between the observatories at Feagh Main and Greenwich was 0h 41m 23.23s of time, and gave some hints about the uneven local shape of the Earth under England and Ireland.

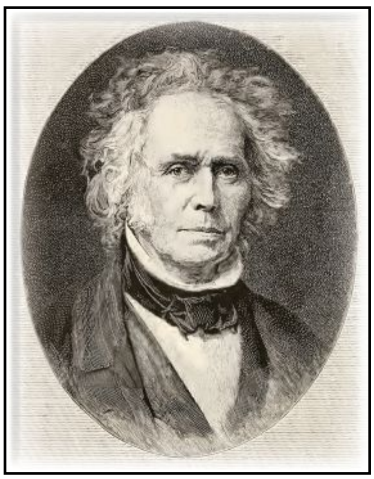
Thus, by the mid-1840s, chronometric expeditions had revised the longitudes of key points from Moscow to Valentia—an east-west distance exceeding 2,000 miles. "It therefore has now become our duty to complete the chain which shall unite us more intimately with the Observatories of the Old World," declared William Cranch Bond, director of the Harvard College Observatory in Cambridge, Mass.[2]

Bond's proposal: nothing less than a grand transatlantic chronometric expedition, spanning another 3,000 miles across the ocean from Boston to England's major port of Liverpool.

### Transatlantic Ambitions

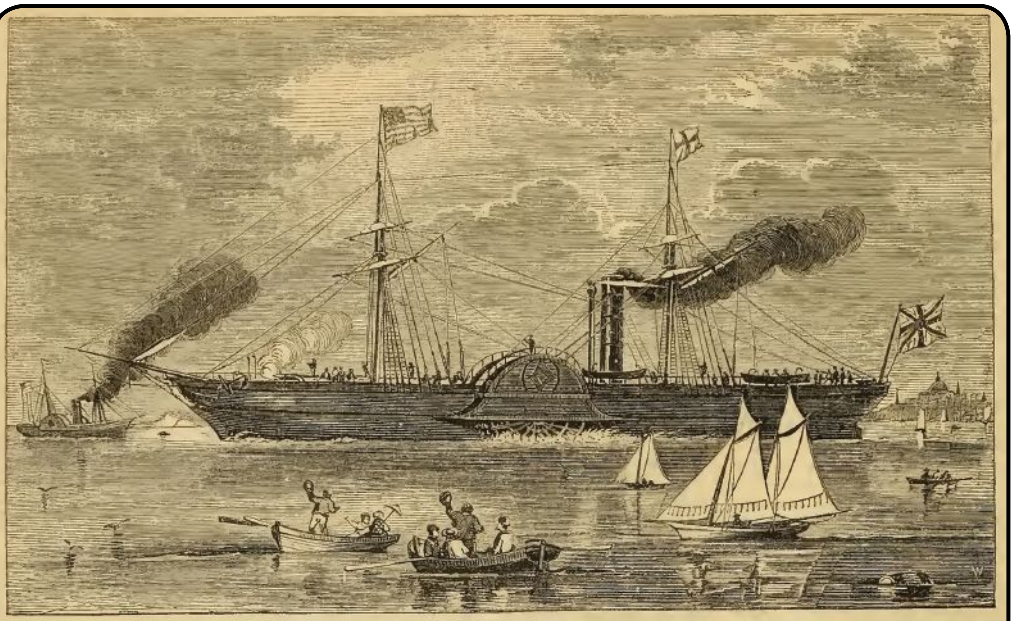
The son of a Boston clock and watch maker, Bond grew up in his father's shop Wm. Bond & Son, proving himself to be mechanically inventive and astronomically adept. In 1815, in the era when marine chronometers were still scarce and difficult to obtain, 26-year-old Bond built the first marine chronometer made in the United States. Soon, he found his excellent mechanisms to be in high demand by Boston sea captains. Eventually, Bond headed the shop, and later was joined by two of his grown sons.

Bond also began offering a valuable new precision service to merchant and government ships arriving or departing Boston Harbor: rating the "going" of their chronometers, and providing exact local time from astronomical observation of sun and stars. Because every early 19th century chronometer was essentially a one-off mechanism, even if its parts were fashioned and assembled by the same artisan, no two were identical. And, although chronometers were then the best mechanical clocks in the world, they weren't perfect: despite bimetallic temperature compensation, their rates slightly varied over days or weeks as springs unwound or as lubricants changed viscosity with age.



*William Cranch Bond (1789–1859), founding director of the Harvard College Observatory, also owned a watch and clock shop Wm. Bond & Son in Boston, Mass. There, he and his sons rated the "going" of ships' marine chronometers, which were used to determine a ship's longitude to aid navigation. After large, fast steamships began regular mail delivery across the Atlantic Ocean, in 1849, Bond hit upon the idea of a grand transatlantic chronometric expedition to definitively measure the longitude of the Harvard observatory with respect to the Royal Observatory, Greenwich. Credit:* Popular Science Monthly 47 *(July 1895), opposite page 289*

*The* America *was the first of a new, larger, faster class of wooden paddle-wheel steamships (249 feet long and over 1,800 tons) that allowed Samuel Cunard's British and North American Royal Mail Steam-Packet Co. to begin offering weekly mail service between Boston and Liverpool. The* America *herself entered service in 1848; she and the five other vessels in her class were in service until the 1860s. For the most part, these were the ships that carried the chronometers for the U.S. Coast Survey chronometric expeditions 1849–51 and 1855. Credit:* Gleason's Pictorial Drawing-Room Companion *6(24): 375, June 17, 1854*




Instead, what mattered was that a chronometer maintained a consistent, steady rate of losing or gaining time, despite temperature changes or jostling during travel on land or sea, so that linear equations could be used to *calculate* the precise time at particular moments.

By 1815, Bond also was closely associated with Harvard College, which that year sent him to Europe to look at European observatories astronomical and instruments. In 1839, Harvard also invited him to head up its first modest observatory (Dana House) and eventually oversee the founding and construction of the major new Harvard College Observatory (still existing). In June 1847, Harvard mounted a refracting telescope with a lens 15 inches in diameter—a virtual twin to the largest telescope in the world at Pulkovo, Russia—and also a large transit circle for positional observations. Harvard provided Bond with a house but no salary from 1839-46, so by day, he continued operating his Boston shop Wm. Bond & Son. Bond also led longitude operations for the U.S. Coast Survey—the nation's largest scientific agency—which was charting many boundaries and coastlines of the New World.

> ***{ Bond's proposal: nothing less than a grand chronometric expedition spanning the Atlantic Ocean }***

In the latter 1830s, steamships were replacing sailing vessels, reducing the average time of a transatlantic crossing from over a month to under two weeks. Several British steamship companies were founded to deliver mail between the UK and ports in Canada and the U.S. But in Britain, ships' chronometers were rated by individual clock and watchmakers around various British ports, and set to local time of unknown accuracy.

In 1844, the brand new Liverpool Observatory at Waterloo Dock was completed with a gleaming new transit instrument for daily astronomical determinations of time. The observatory's primary mission was accurately and officially rating marine chronometers to *Greenwich time* even though Liverpool was 230 miles distant and 12 minutes of longitude west of Greenwich. The new Liverpool Observatory was also a key station in Airy's 1844 chronometric expedition between Greenwich and Valentia.

The next year (1845), the English government awarded a 13-year contract to the British and North American Royal Mail Steam Packet Co., headed by Samuel Cunard, to dispatch a steamship every two weeks carrying mail west from Liverpool to Boston. From 1845-48, Bond experimentally kept meticulous lists of Greenwich time as shown on chronometers of the Cunard mail steamers and calculated the resulting longitude differences.

After Cunard's introduction of a larger, more powerful steamship the *America* in 1848, which immediately set transatlantic speed records, Bond wondered: could fast mail steamers provide a low-cost alternative to the monumental expense of a dedicated U.S. government transatlantic chronometric expedition—which, for completeness, also would yield longitude determinations on eastbound voyages as well?

In early 1849, Bond broached his big idea to John Hartnup, founding superintendent of the Liverpool Observatory, asking for cooperation in making observations and seeking advice re renting or borrowing chronometers. Hartnup immediately obtained promises of support from Astronomer Royal Airy and other key British observatory directors and chronometer makers. Armed with this news, on March 12, Bond wrote to Alexander Dallas Bache, superintendent of the U.S. Coast Survey.

Bache instantly saw the merit of Bond's proposal, well recognizing that the longitude of the Harvard College Observatory in Cambridge was the best-determined point in the nation—indeed, a de facto American prime meridian from which many American longitudes were measured.[7,26] So, things moved fast. By April, Bond and Bache were estimating costs for Coast Survey funding (just over $3,600—equivalent to at least $122,000 in 2018 dollars[3]—primarily for renting and insuring chronometers and paying their cost of passage), to begin immediately for the summer sailing season. The next month (May 1849) Bache wrote out the first check, and Bond sent his son Richard (a partner in Wm. Bond & Son) to England to coordinate British operations.

## Mysterious Errors

By the end of 1849, when operations were ended for the stormy winter season, Bond reported that he and Hartnup had "exchanged" 175 chronometers across the Atlantic. (Note: they did not use 175 unique chronometers, but a smaller number—47 to 60 in the 1849–50 season; 12 or 13 chronometers were carried in each of 14 one-way voyages back and forth across the ocean, yielding the total of "exchanges." Adding to the confusion, both the Bonds and other astronomers often used just the word "chronometers" as shorthand for "exchanges of chronometers.")

But their results revealed an unpleasant surprise: the eastbound voyages consistently showed a longitude difference three seconds of time greater than the westbound voyages. How could that be?

Although this 1849 chronometric expedition was 170+ years ago, Bond's drive to squeeze out every possible source of experimental error for repeatable precision was exactly what scientists and engineers do today. Bond strongly suspected that some temperature difference caused the chronometers to gain or lose time en route. It was well known that diurnal temperatures on land swung through greater extremes than at sea. But why direction of travel seemed to make a difference was mystifying. Bond also wondered about the jostling of the chronometers when they were sent by rail between the Liverpool and Greenwich observatories to obtain true Greenwich time, or by carriage between Wm. Bond & Son in Boston, and the Harvard College Observatory to obtain true Cambridge time.

Clearly, another year of expeditions was necessary. Indeed, there were two more years. During the winters of 1850 and 1851, Bond systematically rated the going of the chronometers at different temperatures, exposing them to Cambridge's subfreezing outdoor temperatures down to 0°F and baking them in ovens up to 105°F. He also subjected them to vibration testing in a horse-drawn carriage pulled over the frozen mud ruts in the road between Boston and Cambridge.

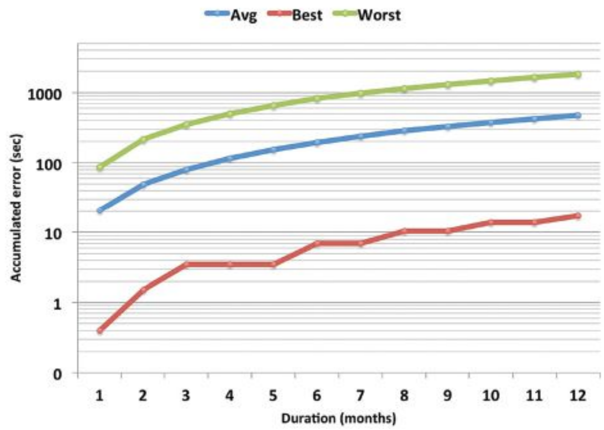
Each year, the Coast Survey's Bache fronted about $4,000 for expenses, and the chronometers were put onto the mail steamers in late spring. Beginning in 1850, Bond detailed a Harvard astronomer to accompany the chronometers back and forth across the ocean, to wind them every day or so, and to take several daily readings of times, temperature, and barometric pressure, thereby eliminating any variability from ships' officers performing those tasks. In 1851, that Harvard astronomer also quantified the "personal equation" (reaction time) of Hartnup in timing transits at the Liverpool Observatory to ensure consistent observing protocols on both sides of the Atlantic. By then, telegraph wires had been installed between Cambridge and Boston, so Harvard time was telegraphed to Wm. Bond & Son, eliminating the need to convey chronometers to the observatory. (It was another decade before the Liverpool and Greenwich observatories were telegraphically connected.)

*Table highlights a few of the most influential international chronometric expeditions up through the U.S. Coast Survey transatlantic expeditions. Over the three years 1849–51, the Bonds sent a total of 92 individual chronometers on 19 one-way voyages both eastward and westward. In 1855, another six voyages were made (three round trips). Note: The Bonds' letters and reports contain discrepancies in numbers of unique chronometers (and in the number of exchanges), not least of all because the rates or other operation of some chronometers proved to be unreliable, so their readings were later rejected; also, the most reliable chronometers were used multiple years. Credit: Trudy E. Bell*

**Table.**
**A Few Major Chronometric Expeditions 1822-55**

| Year(s) | Lead Astronomer(s) | Number of Chronom's | Number of Exchanges | Between which grographical points | Sponsor |
|---|---|---|---|---|---|
| 1822 | John Lewis Tiarks | 15 | | Greenwich & Falmouth, England/island of Madeira | British Admiralty |
| 1823 | John Lewis Tiarks | 24 | | Greenwich & Falmouth & Dover, England | British Admiralty |
| 1824 | Tiarks & Schumacher | 28, 35 | | Altona, Denmark/Greenwich, England/European points | British Admiralty |
| 1820s-30s | Robert Treat Paine | varied | up to 351 | 27 points around Massachusetts (at least 1 per county) | Mass. State Legislature |
| 1833 | Lt. Gen. Fyodor Schubert | 56 | | 3 circuits around the Baltic Sea (several dozen points) | Russian Emperor Nicolas I |
| 1843 | F.G.W. Struve | 81 | | Pulkova, Russia/Altona, Denmark | Russian Emperor Nicolas I |
| 1844 | F.G.W. Struve & O.W. Struve | 86 | | Altona, Denmark/Greenwich, England | Russian Emperor Nicolas I |
| 1844 | George Biddell Airy | 30 | | Greenwich, England/Valentia, Ireland | British Admiralty |
| 1844-48 | William Cranch Bond (informally) | | 373 | Boston,Mass./Liverpool, Eng.: westbound mail steamers | Harvard College Observatory |
| 1849-50 | W.C. Bond/John Hartnup | 44 to 60 | 175 | Harv.Coll.Obs./Liverpool Obs: voyages both ways | U.S. Coast Survey |
| 1851 | W.C. Bond/John Hartnup | 37 | 369 | Harv.Coll.Obs./Liverpool Obs: voyages both ways | U.S. Coast Survey |
| 1855 | W.C. Bond/John Hartnup | 52 | 248 | Harv.Coll.Obs./Liverpool Obs: thermometric exped. | U.S. Coast Survey |

**Survey of 1700 Chronometers, Hartnup (1863)**




*John Hartnup's testing of 1,700 chronometers at the Liverpool Observatory gave an average error of 6 miles in a month or 136 miles in a year (the best ones had a fifth that error while the worst ones had error four times greater). But Hartnup's measurements were made in 1862–63, so in the 1840s likely the average error would have been greater. This modern chart showing the error as seconds of time was devised by retired U.S. Naval Observatory astronomer Richard E. Schmidt, based on tabular data by Hartnup published in the July 1, 1863 issue of The Horological Journal*

In November 1851, Bond wrote a warm letter of thanks to Hartnup and the Liverpool Observatory committee. Then Bond, his son George, and Coast Survey analysts spent four years crunching through all the laborious mathematics (by hand in that pre-calculator age) and writing up a detailed 150-page report. Along the way, brief summaries of their measured longitude difference between the Liverpool and Harvard observatories (4h 44m 30.10s) from the chronometric expeditions of 1849–50–51 were published.

In 1855, Bache supported one last set of chronometric expeditions between Boston and Liverpool, even more stringently quantifying variations in temperature to eliminate any possible east-west longitude discrepancy. For that expedition, Bond also invented a special "thermometric chronometer" without temperature compensation to monitor alongside the regular marine chronometers, to provide an ongoing record of the effect of diurnal variations in temperature on its rate of going during each voyage.


*Astronomical clock (standing) and Bond spring governor chronograph (on table) were displayed at the 1851 Great Exhibition of the Works of Industry of All Nations, held in London's specially built Crystal Palace—an event considered to be the first world's fair. The astronomer (possibly George Phillip Bond) sits at the eyepiece of a small astronomical transit telescope likely similar in size to the one mounted in the temporary observatory atop Feagh Main for the Astronomer Royal's 1844 chronometric expedition between Greenwich, England, and Valentia, Ireland. Credit: Public Domain/The New York Public Library*

### Forgotten Triumph

Altogether, the Harvard and Liverpool observatories recorded 1,065 exchanges—greater than any previous or later chronometric expeditions. The final longitude difference determined between Cambridge and Greenwich was 4h 44m 30.82s. "Cambridge is now the central geographical point of this Continent," exulted George P. Bond. "… Our longitude has, undoubtedly, been investigated with more care than that of any other spot on the globe."[4]

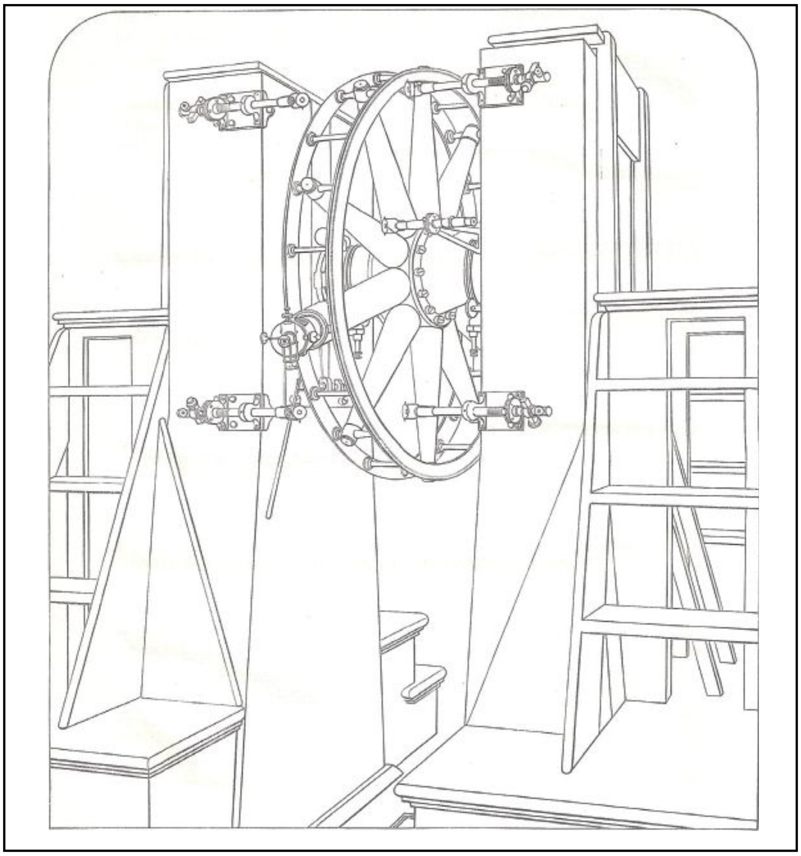
Because its position was so minutely determined, for the next four decades the Harvard College Observatory served as a de facto American prime meridian—until the advent of uniform standard time zones and the official international agreement established Greenwich, England, as the world's prime meridian in 1884. Telegraphic means of determining longitude differences superseded chronometric expeditions as fast as wires could be strung, including undersea transatlantic cables that began providing nearly instantaneous telegraphic communications in 1866 (see "The Victorian Global Positioning System" *The Bent*, Spring 2002).

However, the 1850s—the decade preceding the Civil War—were a time of financial retrenchment for the U.S. Coast Survey. Needing to make tough choices, Bache underwrote the final preparation of reports, but deferred the expense of printing. However, none of the full-length reports prepared were ever published—only brief summaries. So, the rich, fraught history of these monumental chronometric expeditions still lies buried in half a dozen boxes of handwritten letters and report drafts in the archives of Harvard University in Massachusetts and the archives of the U.S. Coast Survey at the National Oceanic and Atmospheric Administration (NOAA) in Washington, D.C.

Nonetheless, well into the early 20$^{th}$ century, chronometric methods of determining longitudes remained a standard tool for the Coast Survey, especially useful in astronomical and exploring expeditions to remote regions without telegraphic communications.

Gratitude is expressed to Richard E. Schmidt—retired U.S. Naval Observatory astronomer who in 2019 published a detailed history of the Liverpool Observatory and has also researched the 1855 chronometric expedition—for very helpful comments on the manuscript, and for providing or suggesting several illustrations and useful sources.

*The large transit circle at the Harvard College Observatory, one instrument used to accurately determine local time from the stars for rating chronometers (among other types of observations), was installed between two piers in November 1848. Made by Troughton & Simms in London, the telescope had a lens of 4¼ inches in aperture and 5 feet focal length. The circles, engraved with angular measurements, were 4 feet in diameter and read with eight microscopes (four are visible on the piers). The Liverpool Observatory was equipped with a slightly smaller transit instrument. Credit:* Annals of the Astronomical Observatory of Harvard College, *vol. 1, part I (1856), p. xlvii*



## *Selected References*


Much of this research is based on unpublished letters and draft reports residing in the Harvard University Archives (in UA V 630.349.1 Box One, in folders mostly categorized by year), supplemented by published reports of the U.S. Coast Survey. To conserve space, only published references for direct quotes are given (readers desiring the full list of 29 references may contact the author).

1 Airy, George B., "Account of the Measurement of the Astronomical Difference of Longitude…from Greenwich to the Island of Valentia…," *Memoirs of the Royal Astronomical Society* 16: 55–174, 1847.

2 Bond, William C., "Report of the Director to the Visiting Committee of the Board of Overseers of Harvard University." 1849. In "History and Description of the Astronomical Observatory of Harvard College." *Annals of the Astronomical Observatory of Harvard College*. vol. 1, part 1, Appendix, 1856.

3 Measuringworth.com, specifically https://www.measuringworth.com/calculators/uscompare/result.php?year_source=1849&amount=3600&year_result=2019 $122,000 is according to the Consumer Price Index, but many other comparators would yield a much higher number. N.B., $3,600 in 1849 was more than double W.C. Bond's salary of $1,500 as director of the Harvard College Observatory, which then had one of the two largest telescopes in the world.

4 Quoted in Stephens, Carlene, "Astronomy as a Public Utility," *Journal for the History of Astronomy* 21: 30, Feb. 1990.


## About the author


*Trudy E. Bell, M.A. (t.e.bell@ieee.org), former editor for* Scientific American *and* IEEE Spectrum *magazines and former senior writer for the University of California High-Performance AstroComputing Center, is author or co-author of a dozen books and 600+ articles. She is a contributing editor for* Sky & Telescope *and an editorial board member for Springer's Historical & Cultural Astronomy series of books.*
*This is her 30th feature for* The Bent.

# Richard Schwartz 2019 Queen Elizabeth Prize for Engineering: GPS

By: **Stuart E. Kirtman**, *New York Iota '88*

*His Royal Highness The Prince of Wales (left) presents the 2019 QEPrize award to Richard Schwartz. Credit to the Queen Elizabeth Prize for Engineering Foundation*

At a December 2019 ceremony held in Buckingham Palace, Tau Bate Richard Schwartz, *NY Iota '57*, received the 2019 Queen Elizabeth Prize for Engineering (QEPrize) for his pioneering work in the development of the Global Positioning System, popularly known as GPS. Using signals transmitted from satellites orbiting the Earth, a GPS receiver can determine its position, and obtain accurate time information, almost anywhere on the planet. Estimated to impact billions of people throughout the world, GPS is one of the greatest advances in global positioning and navigation since the mid-1700s when England's John Harrison devised a rugged, seaworthy clock with sufficient accuracy and precision that it could be used to determine longitude using time-based methods, thus enabling chronometric navigation (**see page 8**).

Awarded biennially, the QEPrize is often considered to be the Nobel Prize equivalent for engineering: its winners are selected by a distinguished panel of judges, it is conferred upon the recipients by the British royal family, and it comes with a substantial sum of money. For their roles in the development of GPS, Prince Charles presented Schwartz and three of his colleagues, Bradford Parkinson, James Spilker, and Hugo Fruehauf, with trophies at a formal ceremony, and the four winners shared a cash payment of GBP 1 million (approximately USD 1.3 million).

The GPS system comprises three main segments: a "Space Segment" consisting of a constellation of satellites located more than 12,000 miles above Earth, a "Control Segment" with centers that issue commands to maneuver the satellites and adjust and monitor their on-board systems, and a "User Segment" consisting of the radio receivers whose positions are to be determined. By decoding specially encoded radio transmissions from the satellites, the User Segment receivers determine the difference in the arrival times of signals from several satellites and use that, along with the known positions of the satellites, to compute the receiver's location (which is typically presented as latitude, longitude, and altitude). To function properly, a receiver must acquire signals from at least four satellites, and Schwartz, a vice president during the 1970s at Rockwell International, and his team were awarded a 42-million-dollar contract to design, build, and place into space the first four satellites that would serve as proof-of-concept to determine the viability of GPS.

Schwartz, who holds a B.E. in mechanical engineering from Cooper Union and an MBA from Pepperdine University, assembled a multidisciplinary group that successfully built and launched the first GPS satellite only 44 months after the contract was awarded and had all four satellites fully operational within nine more months. One of the challenges faced was the need for each satellite to provide an extremely accurate timestamping of its transmissions. Doing this required the use of an atomic clock that could meet stringent size, weight, and performance criteria, and the design of such a timepiece for the satellite was an extraordinary achievement. The four satellites, which contained redundant systems and were built to exacting specifications, not only provided evidence of the likelihood of success of the complete GPS system, but they also demonstrated that it was possible to obtain significant program cost savings by designing satellites with a long lifespan.

GPS receivers were once expensive and large, but as a result of technological advances, their cost and size have been dramatically reduced. Relatively inexpensive receivers that are approximately the size of a thumbnail and are capable of determining their position to within a few meters or better can now readily be obtained, making GPS an affordable, practical, and useful method for navigating by car, boat, and plane, locating cell phones placing emergency calls, tracking shipping containers, studying geological trends, surveying land, creating maps, tracking exercise progress, exploring new locations, aiding search and rescue efforts, and myriad additional applications including many which have yet to be discovered.

After his work with GPS, Schwartz continued with an illustrious career in aerospace. At Rockwell, he advanced to become the Executive VP of their space shuttle program and later the President of their Rocketdyne Division. He subsequently joined the Hercules Aerospace Company as its President and remained in that position until the company was sold to Alliant Techsystems (ATK). At ATK, he served as CEO and Chairman of the Board until his retirement in 2000. Schwartz is a member of the GPS Hall of Fame and the Space Technology Hall of Fame, a Director at Frequency Electronics, Inc. and at Astronautics Corporation of America, and the recipient of the NASA Public Service Medal, the Air Force Quality Award, and the Cooper Union Gano Dunn Award.

More information about the QEPrize can be found at the website *qeprize.org*.