Indian Journal of History of Science (2025) 60:371–381
https://doi.org/10.1007/s43539-025-00187-y

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162 years of rendezvous with the magnetic equator by the Travancore observatory

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Received: 4 January 2025 / Accepted: 17 October 2025 / Published online: 29 October 2025

Abstract
Once a seat of scientific grandeur, the Travancore Observatory showcased 189 years of fruition recently. Meandering through 140 years of administrative handovers and mandate changeovers, a historical look at the observatory's scientific productions unearths geomagnetic discoveries that were never celebrated. Volumes of Travancore productions remain confined as historical accounts of the Kingdom, and the science published in them remains forgotten. The first ground-based mapping of the magnetic equator in southern India was achieved in 1839 through the collaborative efforts of Caldecott and Taylor, who had then served as the directors of the Travancore and Madras observatories, respectively. The southern migration of the magnetic equator on the west coast of India was reported in 1859 by John Allan Broun, who had served as Director of the Travancore observatory from 1852 to 1869. Based on the ground-based magnetic measurements made at the observatory, the epochs of absence of migration of the magnetic equator, its northward migration, and the reversal in the direction of migration of the dip equator can be determined from the analysis of the Travancore productions up to 1941. After the birth of an independent India, the data from the observatory served as the primary reference point for magnetic field calibration for a generation of researchers studying the migration of the magnetic equator in India. By 1999, the magnetic observations at Travancore were stopped. Established by a young king with a vision for the growth of science in his Kingdom, the scientific productions of his observatory laid the foundation for the evolution of present-day flourishing institutions dedicated to full-scale research on meteorology and geomagnetism in India. In the changing world, the Travancore Observatory continues to strive with limited research patronage as an amateur astronomy institute.

Keywords Magnetic equator · Migration · Indian Penninsula · Magnetic dip

1 Background

Nautonier published the first world map with a clearly marked magnetic equator, distinct from the geographical one (le Nautonier, 1603). The Magnetic equator is an imaginary line along which the Earth's magnetic field lines are parallel to Earth's surface, implying that there is no vertical component of the Earth's magnetic field along this line. Thus, all along this imaginary line around the globe, a magnetic needle suspended on a pivot will not exhibit any dip relative to the horizontal component of the Earth's magnetic field. Nautonier constructed a sinusoidal magnetic equator based on a sound geometrical analysis using observations made available to him, which indicated that declination was close to zero on the Canary Islands meridian, with mainly negative values to the west and positive values to the east (Courtillot and Le Mouel, 2007). A careful set of observations in London had allowed William Borough to establish a value of 11° ¼′ E for the magnetic declination there in 1580 (Courtillot and Le Mouel, 2007). Early in 1622, Edmund Gunter, professor of astronomy at Gresham College, measured the declination as 5° 56′E at Borough's original site. Concerned about the instrumental errors in measurement, Gunter did not draw any conclusions from the observations. Henri Gellibrand, a successor of Gunter, repeated Gunter's 1622 observations in 1635 and found an average value of 4° 5′E for declination there (Gellibrand, 1635). Thus, it was established that the magnetic effect of the Earth can change over the course of decades, raising new scientific questions regarding navigation and orientation of the Earth's magnetic field. The Royal Society in London and the Académie des

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Sciences in Paris supported the construction of astronomical observatories, the determination of longitude at sea, and, in some cases, fostered magnetic research. In 1667, members of the Académie des Sciences measured declination on the site of the proposed Paris Observatory, which was completed in 1670 (Gellibrand, 1635).

The first global magnetic survey of the Paramore, conducted under the leadership of Edmund Halley, resulted in famous charts of lines of equal values of declination (isogons, then known as "Halleyan lines") for the Atlantic (1701) and for the world (1702) (Jonkers, 2000). They were based on some of Nautonier's ideas, but on a larger number of measurements. In 1722, George Graham discovered the daily or diurnal variation of declination. In 1741, Graham in London and Andreas Celsius in Uppsala observed simultaneous perturbations, based on five years of daily measurements of declination (Arago, 1854). In 1773, the Academy of Sciences offered a prize to whoever would design a magnetic needle that would show the true magnetic meridian and the tiny diurnal variation. The prize was won in 1777 by Charles-Augustin Coulomb with his remarkable torsion balance (Stern, 2002). This served as the foundation of all magnetic instruments for the next two centuries.

Around 1780, Horace-Benedict Necker de Saussure noted the anomalies which perturb compass readings in some mountains and attributed them to iron deposits. He tried to measure the attractive force using a sort of primitive magnetometer and noted that "heat is the most general cause of variations of the magnetic force, in that it increases upon cooling and decreases upon a temperature rise (Fournet, 1848). Alexander von Humboldt and botanist Aimé Bonpland, during their expedition (1799–1803) to South America, located the magnetic equator in 1802 while recrossing the Andes near Caramaca. Humboldt's measurement of the Earth's magnetic intensity at this spot served as a reference point for all geomagnetic measurements for the next half-century. His magnetic readings, taken from latitudes 52° North to 12° South, clearly showed that magnetic intensity increased with latitude. He coined the terms "isodynamics" (lines of equal magnetic intensity), "isoclines" (lines of equal magnetic dip), and "magnetic storm" (von Humboldt, 1855).

In 1807, von Humboldt performed relative measures of horizontal intensity in Italy with Louis-Joseph Gay-Lussac and was able to draw the first real isodynamical lines. In 1828, a special magnetic hut was erected. Humboldt and a team of assistants recorded the fluctuations in the magnetic declination every hour, both day and night. He was interested in determining whether the variations were of terrestrial origin or depended on the position of the Sun (Botting, 1994). To this end, he sought a chain of geomagnetic observation stations spanning the entire globe. In 1829, in St. Petersburg, he convinced the Russian authorities of the scientific advantages to be gained from setting up a series of magnetic and meteorological stations across Europe and Asiatic Russia. Within six years, a number of such stations were in operation all the way from St. Petersburg to Peking and Alaska. The USA already had a network of similar stations, and Gauss had arranged another network of observatories, known as the Gottingen Association, across Europe, from Ireland to Germany. Humboldt realised that to complete the round-the-world circle, he needed to persuade the British Government to establish stations in their territories overseas and in April 1836, he wrote a letter to the Duke of Sussex in which he proposed that permanent stations should be set up in Canada, St Helena, Cape of Good Hope, Jamaica, Ceylon and Australia.

In 1831, the Committee of Mathematical and Physical Sciences of the British Association for the Advancement of Science (BAAS) urged measurements of magnetic inclination ("dip") and intensity at points throughout England, Scotland, and Ireland (Cawood, 1979). At their 1832 annual meeting in Oxford, the BAAS called for an international magnetic venture on par with the growing network of Continental observatories organised by the naturalist Alexander von Humboldt and the mathematician and astronomer Carl Friedrich Gauss (Goodman, 2016). Astronomer John F.W. Herschel and the natural philosopher William Whewell, along with Edward Sabine, lobbied for a global system for measuring geomagnetic phenomena. They proposed investigations including a voyage to the Antarctic and the creation of a network of magnetic observatories to measure magnetic variation at far-flung points around the planet. By 1835, cooperative agreements with the Académie des Sciences in Paris and the East India Company substantially broadened the scope of the project, enabling the mounting of a southern expedition and the establishment of a set of fixed observatories in England and the colonies (Cawood, 1979). In 1833, Sabine began working alongside Humphry Lloyd, who had been engaged in a magnetic survey of Ireland. Sabine and Lloyd's network of magnetic observers eventually expanded to include the Royal Society, which was also working closely with the BAAS in presenting proposals for magnetic research to the British government.

British scientists lobbied for and successfully obtained funding for expeditions to measure geomagnetic phenomena and to build geomagnetic observational outposts in the colonies. Financing for the geomagnetic scheme was renewed at three-year intervals, in 1842, 1845, and 1848. Following this, magnetic observatories were established in many British colonies. Observatories were established in Canada, the South Atlantic, Tasmania, and India. Edward Sabine oversaw four of the new observatories. He established the duties of personnel in the magnetic observatory in terms that are far from obsolete today. He made sure that the full magnetic vector was measured and carefully separated (Chapman &

Bartels, 1940). In 1852, Sabine recognized that magnetic variations could be divided into a regular diurnal cycle and an irregular portion. The irregularity correlated very closely with fluctuations in the number of sunspots, whose cyclic nature had been discovered in 1844 by the German amateur astronomer Heinrich Schwabe. Sabine was the first to recognize that solar disturbances affected the Earth's magnetic environment. On April 6 1852, he announced that the Sun's 11-year sunspot cycle was "absolutely identical" to the Earth's 11-year geomagnetic cycle. From these observations, Sabine concluded that magnetic disturbances vary in intensity in parallel with sunspot variations (Edward, 1852).

2 Magnetic observatories of the British East Indian company in the Indian peninsula

The British East India Company had a profound influence on the magnetic survey in India. Captain Thomas Jervis had been pressing the Company's directors since early 1838 to support a magnetic survey in central Asia. In 1838, he wrote to James Melville, Chief Secretary at the East India Company, requesting sufficient funds to cover the cost of equipping the observatories in the Raj, as Lloyd had specially trained those bound for these observatories in Dublin before dispatching them to their posts (Carter, 2009). India's participation in the science of geomagnetism was initiated in 1836, when the country became a member of the Göttingen Magnetic Union (GMU), which was formed in 1836 by Gauss and colleagues (Gauss, 1839). Under the aegis of the GMU, the East India Company established three magnetic stations at Madras (Chennai, 1841), Simla (1841), and Travancore (Thiruvananthapuram, Trivandrum, 1841) (Brande, 1843).[1] In 1845, BAAS made recommendations that led to the closure of the East India Company's physical Observatory at Simla (Ratcliff, 2016).

An observatory was established in 1823 by the East India Company at the southern end of an island called Colaba (close to the present city of Mumbai) (Lakhina & Alex, 2007). It was furnished with some magnetic instruments as a result of the untimely death of an officer who was responsible for the transport of those instruments to Aden, now in Yemen (Orlebar, 1846). Arthur Bedford Orlebar, professor of astronomy at Elphinstone College, Mumbai, took possession of these instruments and was awaiting advice from Captain Boileau on how to operate them, who was then the superintendent of the Simla Observatory (Orlebar, 1846). John Caldecott, the Director of the Travancore Observatory, who was then passing through Mumbai, familiarized Orlebar with magnetic instrumentation techniques (Gawali et al., 2015). The first magnetic observations from Colaba were recorded in 1841–42. The magnetic observations from Colaba were affected by modernization. Continuation of magnetic studies was achieved by establishing the Alibag observatory, which is located near Colaba. Geomagnetism studies are kept up to date at the Alibag observatory, and they continue to contribute to the International field of geomagnetism.

The Madras Observatory (in modern Chennai) can be claimed as India's first modern astronomical observatory. It was established as a private venture by William Petrie in 1786, an officer in the British East India Company (Salwi, 1988). Later, from 1792, the observatory was managed by the East India Company 'to promote the knowledge of astronomy, geography and navigation in India'. Magnetic studies were conducted at the observatory between 1822 and 1881 (Lakhina & Alex, 2007). Hourly magnetic observations were recorded at the observatory from 1822 onwards and continued until 1861, when it was decided to record only two observations per day at suitable hours (Jayakrishnan, 2023). T.G. Taylor, who served as the Director of the Madras Observatory from 1830–1848, prepared a catalogue of 11,015 stars in 1844, popularly known as the 'Madras Catalogue' (Salwi, 1988). T.G. Taylor collaborated with John Caldecott, the Director of the Travancore Observatory, to make observations on the direction and intensity of the terrestrial magnetic force during 1837–1838 (Taylor & Caldecott, 1839). The daily magnetic observations were further reduced in 1875, when the bifilar magnetometer, the only instrument in use, was damaged. The magnetic observations were finally discontinued at Madras in 1881 (Lakhina & Alex, 2007). The works at the Madras Observatory were gradually shifted to Kodaikanal during the period 1895–1900, with observations at Madras being confined to the measurement of time, while Solar physics became the mainstay of the observatory at Kodaikanal. During this transition, the observatory was to come under the control of the Government of India, rather than the Government of Madras, as it had been for a century earlier. By 1971, the observatory had been converted into an autonomous research Institute, known henceforth as the Indian Institute of Astrophysics, which the Government of India wholly financed.

3 First mapping of the magnetic equator in Southern India

Travancore was a kingdom located in the southernmost tip of the Indian peninsula, ruled by a single family with an unbroken lineage dating back to 875 CE. It reached its zenith in the early eighteenth century, spanning most of the area south of the present-day state of Kerala in India. Born in

[1] Simla (India) Observatory, Meteorological Observations Made at the Magnetic and Meteorological Observatory at Simla During the Years 1841-1845: Under the Direction of Lieut.-Colonel J.T. Boileau.

1813, Swathi Thirunal Rama Varma assumed full powers as the ruler at the age of 16 and reigned as the Maharajah of Travancore from 1829. In the early 1830s, the young king met John Caldecott, an Englishman working as a commercial agent for the Government of Travancore in Allapuzha. Caldecott had his own personal arrangements for studying astronomy. Caldecott's descriptions of his observations of the various movements of the heavenly bodies and their close correspondence with the calculations of Hindu astrology, were identified by the Maharaja who desired a thorough investigation of these sciences. Caldecott was appointed as His Highness' astronomer and was made the Director of the Observatory to be started at Thiruvananthapuram (TVPM) (formerly known as Trivandrum and spelt as Trevandrum), the capital city. The reason for an observatory at TVPM was that the institution was intended to give impetus to science education among his people, and the Maharaja desired that his country should participate with European nations in scientific investigations. The TVPM observatory was established on the Latitude 8° 30′ 32″ N, Longitude from Greenwich at 5 h 7 m 59 s E, at a height of 195 feet above sea level on the highest hillock in the city. Construction of the building began in 1836 and was completed by mid-1837. Caldecott started making observations in July 1837, using his own instruments. Several portable instruments belonging to Caldecott were put into use simultaneously, and a system of meteorological observations was initiated at the same time (July 1837).

Taylor obtained a dipping needle from Captain Moresby in 1837, which had been provided to him by the Geographical Society of Bombay for making observations along the coast of India. He decided to make observations in a line at right angles to the latitude or along the coast, starting from Ongole (lat. 15° 12′ N), proceeding southward, taking measurements at intervals of 20 to 30 miles up to Kanyakumari (formerly known as Cape Comorin) and then proceeding north along the western coast to Goa. He advertised the need for assistance to make these observations, which was responded to by Caldecott. Taylor immediately made arrangements, and they agreed that Caldecott would take measurements on the western coast and Taylor himself would take the measurements on the eastern coast. From August 1837 to December 1838, Caldecott conducted a magnetic survey along the eastern and western coasts of the Indian Peninsula. Starting from Chennai (formerly known as Madras) on July 23, 1837, Taylor moved southward and had a rendezvous with Caldecott on August 2, 1837, at Tharangambadi (formerly Tranquebar). Tranquebar was established in 1620 as the first Danish trading post in India. Caldecott started his magnetic observations from Tharangambadi (a town in the Mayiladuthurai district of the Indian state of Tamil Nadu) where the magnetic readings were taken in the guard room and top of a house from August 7 to August 9 1837 by Taylor and Caldecott (1839)]. The magnetic dip was measured to be ~ +2° 8′. On August 12th and 13th, Caldecott, along with Taylor, conducted measurements in an open shed at Nagapattinam (formerly spelt as Nagapatnam), a town 32 km south of Tharangambadi, and found the dip to be +2°31′. Interestingly, Taylor had made measurements at the verandah of the hospital at Nagapattinam on October 2 1837 and observed it to be +1°43′ 45″. On August 13 1837, they also managed to measure the dip at Mannargudi (formerly spelt as Manargoody) at a location about 53 km to the west of Nagapattinam as +1° 4′ 41″. The study's location is described as the missionary bungalow in Nagapattinam. On August 14, they moved southward to Pattukkottai (formerly spelt as Puttucottah) and measured the dip to be 0° 52′ 37″ at the veranda of a choultry. On August 15, they moved further south by ~46 km and measured the dip to be 0° 7′ at Manamelkudi (formerly spelt as Munamalegoody) at the veranda of a choultry there. On August 16 they measured the dip to be 0° 4′ 15″ at a place named Kalehennary (present name not identified) at the veranda of a choultry there. The coordinates of the measurement are marked as 9°10′ N and 79° E, which presently appear to be in the ocean, approximately 3.7 km off the Karankadu beach. They measured the dip to be –1° 28′ 37″ at Ramanathapuram, also known as Ramnad, on August 17 at the veranda of the commanding officer's quarters. They continued to move south, making observations every day, at intervals of about 40 km. Measurements were recorded at Chinnoor (Carryshandy- 9°11′ N, 78° 27′E) (August 20) (dip (δ) = – 1°51′15″), Vadanatham (Vadinatum—August 21) (dip (δ) = – 1°37′ 31″), Sekkarakudi (Powani- 8°49′ N, 77° 57′ E (August 22) (declination (δ) = – 2°43′ 54″), Palayamkottai (Pallamcottah -23 Aug) (dip (δ) = – 1°50′ 26″), Nagracoil (August 25) also spelt as Nagarkovil (dip (δ) = – 3°54′ 26″), and at the Meteorological bungalow of Thiruvananthapuram (August 28, 5,13 Sep) (dip (δ) = – 3°10′ 26″, – 3°4′ 4″, – 3°10′ 56″).

As per the arrangement made between them, Caldecott alone continued the magnetic measurements along the western coast. He conducted measurements at Kozhikode (formerly known as Calicut) (November 4) (dip (δ) = +1°36′ 15″, +1°13′ 8″), Ponnani (formerly spelt as Penaney) (November 5) (dip (δ) = +1°3′ 8″), Chettuva (formerly spelt as Chetwaye) (November 6) (dip(δ) = +1°3′ 26″, +1°16′ 15″, +1°17′ 30″), Bolgatty (formerly spelt as Balghatty- 9° 59′ N, 76° 16′ E) (November 8) (dip (δ) = 0°31′ 34″, 0°14′ 4″, 0°18′ 5″), Alappuzha (or Alleppey) (formerly spelt as Allepee) (12, 13 November) (dip (δ) = +2°12′ 49″, +1°59′ 41″, 0°57′ 49″, +1°1′ 15″), Kollam (formerly known as Quilon) (November 15) (dip (δ) = – 2°28′ 8″), and Thiruvananthapuram (November 20) (dip (δ) = – 2°41′ 53″, – 3°13″ 11″). Caldecott repeated his measurements in 1838 starting from Thiruvananthapuram (December 15) (dip (δ) = − 3°24′ 4″), Kollam (December 15) (dip (δ) = − 2°28′ 8″), Alappuzha

(December 20) (dip (δ) = − 2°30′19″), and ending at Bolgatty (December 21) (dip (δ) = 0°21′18″). In the meantime, Taylor made magnetic dip measurements on his own on some occasions and in collaboration with Captain D. Bethune on other occasions, along the east coast north of Chennai. He repeated these measurements in 1838 and 1839 at some of the stations.

By February 1839, a complete data set was ready based on the efforts of Taylor and Caldecott, which resulted in the production of the first chart of the isoclinal lines for southern India for CE 1838 as shown in Fig. 1, with the magnetic

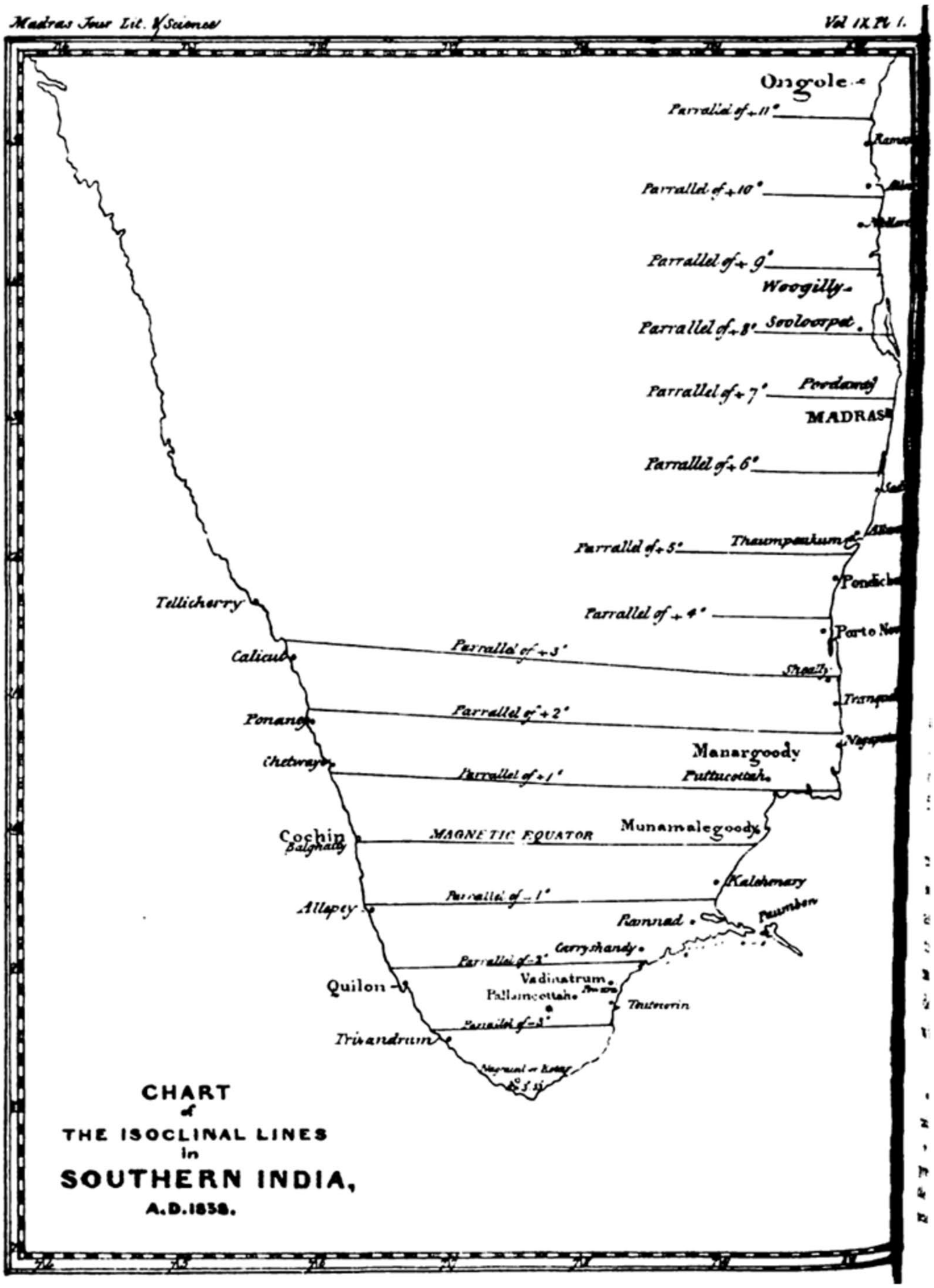

Fig. 1 Map showing the magnetic equator passing through the eastern and western coast of the Indian peninsula prepared by Taylor and Caldecott published in 1839 in the *Madras Journal of Literature and Science* volume IX

equator passing through Bolgatty (located in Cochin) on the western coast and Manamelkudi on the eastern coast (Taylor & Caldecott, 1839).

Lieutenant Ludlow Engineers recorded the dip of the magnetic needle at seven locations on the east coast of south India which were originally measured by Taylor in 1838 (Ludlow Engineers, 1844). The measurements were conducted in 1842, 1843 and 1844. The magnetic dip equator based on these measurements was identified to be at Pattukkottai (formerly spelt as Poothocottah) on the latitude 10° 22′ 50″ N and longitude 78° 52′ 51″ E with a mean dip of 0° 57′. The findings of Ludlow, as represented in Fig. 2, reproduced from the Madras Journal of Literature and Science, represent the position of the magnetic equator on the east coast during that period. Ludlow estimated the annual increase in the mean dip as 2′ 5″ based on the monthly measurement of magnetic dip data recorded at the seven stations during the three years. They were then reported to be the effect of local attraction on the dip needle occurring from geological formations. Today, one needs to recognise the data collected by Ludlow as the first direct evidence, based on ground measurements, proving the shift of the magnetic equator on the east coast of the Indian Peninsula, although it was not interpreted as such a phenomenon in 1844.

4 Travancore productions: the astronomical ephemeris, travancore almanac and the travancore directory

Starting in 1837, the astronomical ephemeris had been prepared at the Observatory by Caldecott at the desire of the King of Travancore, with the view of enabling students in Astronomy to bring their theoretical knowledge into practical use, by providing them all the data and tables necessary for the computation of the most important problems in that science. The very first volume of 1837 contained explanations on how to use the data and how calculations are to be made. The next volume, published in 1838, was based on the same plan but contained more data on stars, solar eclipses, and planetary motion. Caldecott travelled to Britain in 1839 and returned in 1841. The fourth edition of the Astronomical Ephemeris for the year 1841 was prepared by G. Sperschneider, who was the superintendent in charge of the Observatory during Caldecott's absence. These four volumes of the Astronomical Ephemeris did not contain any meteorological or magnetic data. A temporary magnetic observatory at the Trivandrum observatory was started in May 1841, immediately upon Caldecott's return from Britain. Furnished with a vertical force magnetometer, a permanent magnetic observatory was started in October 1841. Edward Sabine, at the 1841 BAAS meeting, reported that Caldecott had sent him data relating to an unusual magnetic disturbance observed at Trivandrum on September 25, 1841. Sabine calculated the magnetic declination based on a magnetic dip of (δ)=− 2°50′ for Trivandrum and found similarity in the magnetic disturbance observed there to that observed at Toronto, St. Helena, and the Cape of Good Hope (Edward Sabine, 1842, p. 340).

In 1858, at the meeting of the British Association for the Advancement of Science, Brown reported that he had examined the magnetic data collected in 1844 by Caldecott and observed that corrections for temperature were not made, nor were the coefficients calibrated (Broun, 1859, p. 30). After a year of analysing the data, he found that the observations made by Caldecott at Trivandrum agreed with his own observations at Makerstoun. At the BAAS meeting of 1859, Broun reported on the survey of the magnetic dip in the Travancore kingdom conducted by selecting stations along the line of coast, at distances 25 to 35 km apart, far from the chain of the Ghats, at flat locations, covered in many places by backwaters or lagoons (Broun, 1860a, 1860b, 1860c, p. 27). He stated that the study was undertaken at the expense

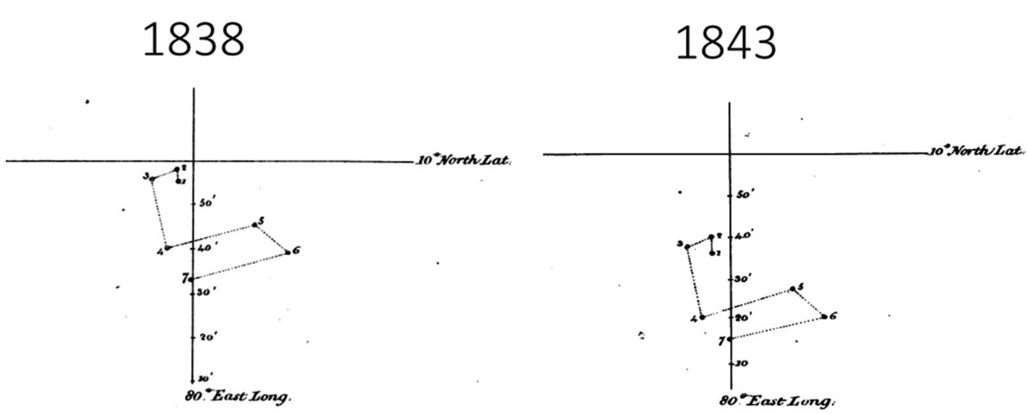

Fig. 2 Position of the magnetic equator deduced from observations of dip needle at the same seven stations measured by Taylor in 1838 and by Ludlow in 1842, 1843 and 1844 and published in the *Madras Journal of Literature and Science*, volume 30, p. 195

of His Highness the Rajah of Travancore, for the purpose, in the first instance, of determining the exact position of the magnetic equator (which passed through his territory) and to study the variations of magnetic intensity about the line of no inclination. The instrument employed was the theodolite magnetometer of Dr Lamont. He observed that the magnetic south inclination, instead of diminishing regularly from Cape Comorin northwards to the line of no dip, decreased over a distance of ~ 48 km, increased over a similar distance, and then decreased again. The same irregularities were observed north of the magnetic equator, which was located ~ 144 km north of TVPM at Cherthala (formerly spelt as Shertally) (Broun, 1860a, 1860b, 1860c, p. 20). The geographical coordinates of the location at Cherthala, where the measurements were made, are recorded as 9°41′43"N and 76°24′50"E. Measurements were repeated at Cherthala from March to April 1858, from September to December 1858, and from March to April 1859.[2] The survey was extended by Broun on his way to Europe by observations at stations further north along the west coast of India, at Kodungalur (presently Kodungallur), Kalikut (presently Kozhikode), Mangalur (presently Mangalore), Goa, Rutnagherri (presently Ratnagiri), Bombay (presently Mumbai), and Aden (in Yemen). From this and the first part of the survey, he found that the horizontal intensity was nearly the same from Cape Comorin to Bombay. In another report made that same year at the BAAS, he reported that the magnetic dip at TVPM was 2.50° south (Broun, 1860a, 1860b, 1860c, p. 21).

Though the analysis of the data collected by Broun is not in the scope of this article it has to be mentioned that a look at the tables showing the diurnal variation of the magnetic field which was collected hourly at the observatory during the tenure of Broun shows that at 11:30 am local time on September 2 1859, the intensity of the field was the highest ever recorded in the history of the Travancore Observatory. The analysis of the data has yielded new information on the Carrington event and marks a new leaf about the history of the Trivandrum observatory. As the observatory was closest to the equatorial electrojet during August–September 1859, the data provides an opportunity to recalibrate the impact of the coronal mass ejection on Earth's magnetic field intensity during that period (Jayakrishnan et al., 2025).

From 1878 onwards, a new volume titled "Travancore almanac" containing reports from the observatory, citing meteorological and magnetic observations, is available in the archives of the state library. This volume was published yearly up to 1901. The Travancore almanac was essentially an annual financial report of the Travancore Kingdom, detailing the rules of taxation, profit, and loss for each institution, as well as the governance structure of the Kingdom. Every volume contained a detailed report from the observatory with the specific values of the magnetic inclination and declination measured at the Trivandrum Observatory. Meteorological observations were also documented in the Almanac. From 1905, the title of the volume was changed to Travancore Almanac & Directory and began to be printed on account of the Government of His Highness the Maharaja of Travancore. The title of the volume was again changed to The Travancore Directory in 1938, and the publication continued until 1944. The Travancore Directory of 1944 included only meteorological data, and the magnetic data were absent.

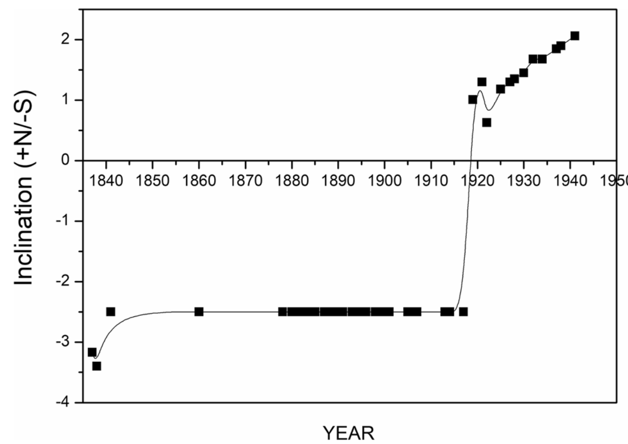

Fig. 3 Plot of the Magnetic dip recorded at the TVPM observatory for the years 1838 to 1941

Between 1878 and 1917, the magnetic dip is recorded as 2.50° south in all volumes of the listed Travancore productions. Instances of the dip equator remaining stationary at different locations of the Earth were reported in scientific journals later in history. Rangarajan and Barreto (2000) demonstrated that in the American sector, the dip equator, centered at 30° E longitude, remained stationary for over 100 years between 1900 and 2000 at 10° N. In the Travancore Almanac & Directory for the year 1919, the magnetic dip at TVPM was recorded as 1° 5′ based on the north-end dip of the needle. It is stated that the dip was observed to be increasing annually at the rate of 6.7 min. For the year 1921, the magnetic dip was recorded as 0° 38′ and the dip was stated to be increasing annually at the rate of 3.3 min. For the subsequent years, the magnetic dip was observed to increase annually at a rate of 3.3 min.

[2] Observations of Magnetic Declination made at Trevandrum and Agustia Malley in the Observatories of His Highness the Maharajah of Travancore, G.C.S.I In the Years 1852 to 1869. Being Trevandrum Magnetical Observations, Volume 1. Discussed and Edited By John Allan Broun, F.R.S., Late Director of the Observatories. (Printed by Order of His Highness the Maharajah.) London: Henry S. King & Co. 1874'. Overleaf reads 'Printed by Neill and Company, Edinburgh'.

The Travancore Observatory was divided into two sections in 1927. The Astronomical section was placed under the charge of the Government Astronomer, Dr H. Subramani Iyer (1927–1941) and the Meteorological section under the Government Meteorologist, Mr Sivaramakrishna Iyer. In 1937, the University of Travancore was established by the Maharaja of Travancore, Sri Chithirathirunal Balarama Varma [Kerala University Archives]. On August 17 1939, the Observatory was transferred to the control of the University and functioned as a unit of the Central Institute of Research.[3] In 1940, the meteorological and astronomical sections were merged. The Observatory then, primarily attended to astronomical observations, calendar computation, and the daily collection of data on rainfall. By the year 1941, the magnetic dip was reported as 2° 4′ in the Travancore Directory. Figure 3 represents a plot of the magnetic dip recorded at the TVPM observatory for 103 years, starting from 1838, by John Caldecott, to the one for the year 1941, published in Travancore Productions.

5 Independent India

The Travancore Kingdom became part of the Indian Union in 1947. The Travancore royal family remained as the titular head of the state till 1949. The Meteorological section of the Observatory was taken over by the Government of India in 1951. The state of Kerala was formed on November 1 1956. A magnetic observatory commenced operation in the Meteorological Station in 1957. In 1961, the National Geophysical Research Institute (NGRI) was started, and scientific teams from NGRI used magnetic observations from the Observatory to map the magnetic equator. The Indian Institute of Geomagnetism (IIG) was given full-scale mandate in 1971 to pursue geomagnetic and allied field research. IIG was given administrative control over the Magnetic Observatory, and they established an independent office near the seashore, away from the Travancore Observatory, which was named the Trivandrum Magnetic Observatory (TMO). The geographic coordinates of the TMO were reported as 8.5° N and 77° E (Geomagnetic Latitude -1.1° Longitude 146.4 E) in 1977 (Srivastava & Abbas, 1977). Rangarajan reported that the coordinates of TMO as 8° 29′ N and 76° 57′ E (Geomagnetic Latitude 1.2° S Longitude 146.4°E) in 1994 (Rangarajan, 1994). TMO remained operational till the year 1999. Scientific teams from IIG conducted ground-based surveys for the dip equator every epoch. They corrected the data using the *Z*-standard at TMO, which played a crucial role in determining the nature of migration of the dip equator.

Based on isomagnetic charts and repeat magnetic observations at field stations Chatterjee et.al. pointed out that the magnetic equator in the Indian region had shifted towards the south from the year 1909 to 1920 and from then on it steadily shifted northward and in 1965 the dip equator passed very near 8° 43′ 30.65" N latitude and 77° 41′ 4.27" E longitude (Tirunelveli) (Chatterjee, 1970). Sanker Narayanan and Ramanujachary from NGRI reported in 1971 on the ground location of the magnetic dip equator based on measurements conducted at stations located ~ 4 km apart along the geographical north–south direction (Narayanan & Ramanujachary, 1971). They used a zero-balance magnetometer from the Hyderabad Magnetic Observatory of the National Geophysical Research Institute for their field measurements conducted between October 11 and 14, 1970. The equipment was checked against the *Z*-standard of the Trivandrum Magnetic Observatory after mapping along the Adoor-Kottarakara-Trivandrum traverse and with the Z-standard at Hyderabad upon completion of the studies. They identified the geographic coordinates of the dip equator to be along the line 8°49.6′ N, 77° E (Thumpamanthody, Kerala), 8°54.1′ N, 77°30′ E (Naranapuram, Tamil Nadu) 8°58.5′ N, 78° E (P.Duraiswamipuram, Tamil Nadu).

Murty et. al. from NGRI conducted a geomagnetic survey in 1981 to identify the position of the dip equator in the Indian region (Murty et al., 1984). They found the dip equator about 24 km south of its 1971 position along the 77.5° E meridian. Absolute values of the total field (F) and its vertical component (Z) were measured using a proton precession magnetometer (PPM) and a digital fluxgate magnetometer, respectively, at 520 stations with a spacing of 8 to 10 km. From the F and Z observations at each station, the horizontal component (H) values were computed. The H and Z data were then corrected for diurnal magnetic variation, using the hourly values from the magnetic observatories at Trivandrum, Etaiyapuram, and Annamalainagar. They identified locations with near-zero dip values spread over a region of about 10′ in latitude (approximately 18 km), signifying that, in India, there exists a dip-equatorial belt.

In 1991, another ground magnetic survey was conducted using a zero balance magnetometer (BMZ) for Z and a proton precession magnetometer for the total field intensity F by Rangarajan et. al. from the IIG [38]. The survey was conducted along three north–south traverses running along the west coast, east coast, and the spine of peninsular India between 8 and 8.5° N geographic latitudes. The survey team conducted spot observations of Z at intervals of 4 to 5 km, covering approximately 57 locations over three days between February 12 and February 14, 1991. These observations were reduced to the midnight reference level by allowing for the difference in diurnal variations in the Z

[3] Science News a century ago The observatory of the Rajah of Travancore, Nature 144, (1939): 952.

component, as observed at the Trivandrum magnetic observatory. The latitude corresponding to zero Z was determined independently for each of the traverses and was found to be 8.23°N, 8.28° N, and 8.32° N, respectively (Rangarajan & Deka, 1991). They found that the average rate of southward migration of the dip equator was ~ 4 km/year between 1971 and 1991, and that the migration in the latter decade was faster, at around 5 km/year, compared to the 1971–81 era.

Nagarajan et al. from IIG, in 2010, provided a retrospective study on the migration of the dip equator using data available from the Trivandrum magnetic observatory for the period 1957–1999, along with data from 10 other Indian magnetic observatories (Nagarajan et al. 2016). They observed that the dip equator's southward migration rate had increased after 1990. Differences were observed between the inferred location of the dip equator for epochs between 1970 and 2010, and the location derived from IGRF models for the same epochs. There was no evidence for the commencement of northward migration of the dip equator (Nagarajan et al. 2016).

The Trivandrum Magnetic Observatory was closed in 1999 primarily due to urbanization and electromagnetic interference from the growing city of Thiruvananthapuram (Trivandrum). As the city expanded, the increasing electrical activity and infrastructure began to interfere with the sensitive magnetic measurements being taken at the Observatory. To ensure the accuracy and reliability of geomagnetic data, it was decided to relocate the Observatory to a more remote location with less electromagnetic noise. This led to the establishment of the Tirunelveli Magnetic Observatory in 1996, which continues to operate and provide valuable geomagnetic data.

6 Conclusions

The Trivandrum observatory, which started in 1836 with a vision for the development of science in a princely state, underwent systemic administrative changes over 140 years as an independent democratic country evolved around it. However, the later generation of political leadership failed to recognise the Observatory's contributions to global science. While the princely state facilitated the Centre with an infrastructural and instrumental arsenal that was far ahead of its time relative to other observatories under the British East India Company, the successive Government policies were never in tune with nurturing the institution into the twentieth century. The Travancore productions remain confined as historical accounts of the princely state, and the science published in them remains forgotten.

Although magnetic data was collected by Caldecott from 1837 and communicated at the BAAS meetings, it failed to appear in the scientific production of the Travancore state. One has to read between the lines to understand that Caldecott was communicating to Sabine the results of his labour on magnetism, although the cost of it was being borne by the Travancore kingdom, and it was not reaping any benefits from the magnetic observations. It would also appear that, since Bolgatty was part of the Cochin kingdom and having had identified the magnetic equator outside the boundary of the Travancore kingdom, Caldecott may not have considered it a subject worth exploring for the Travancore state at that point in time. It must be acknowledged that the first ground-based mapping of the magnetic equator in India was conducted by Caldecott and Taylor, both of whom were directors of astronomical institutions at the time. Their findings indicate that the dip equator was located near 10°N latitude during the years 1838–39, as marked in Fig. 4. The collaborative efforts between the two researchers resulted in the first ground-based mapping of the magnetic equator in the South Indian Peninsula.

One also needs to recognize that the first proof of the southward migration of the magnetic equator in India was identified by Broun. The zero magnetic dip identified by Caldecott in 1837 at Bolgatty (9° 59′ N, 76° 16′ E) had shifted south by 40 km over 21 years and was observed to be at Cherthala by Broun in 1859. However, there are no records of any measurements made by Broun on the eastern coast of India. The identification of the location of the magnetic dip zero on the western coast, close to 9°41′43"N latitude and 76°24′50"E longitude, remains a significant finding by Broun. Based on Broun's report, we can estimate that the

Fig. 4 Magnetic equator identified in 1839 by Caldecott and Taylor along the 10° N latitude marked as white line. Locations of the magnetic dip zero were recorded at Bolgatty and Manamelkudi in 1839, Cherthala in 1859 and at TVPM in 1921 (pin dropped in yellow color). Red-colored pins marks joined by yellow line mark the magnetic equator, mapped by the National Geophysical Research Institute (NGRI) in 1970 using facilities of the Trivandrum Magnetic Observatory. Violet-colored pins mark joined by yellow mark the magnetic equator, recorded in 1991 by IIG, which administered the Trivandrum Magnetic Observatory

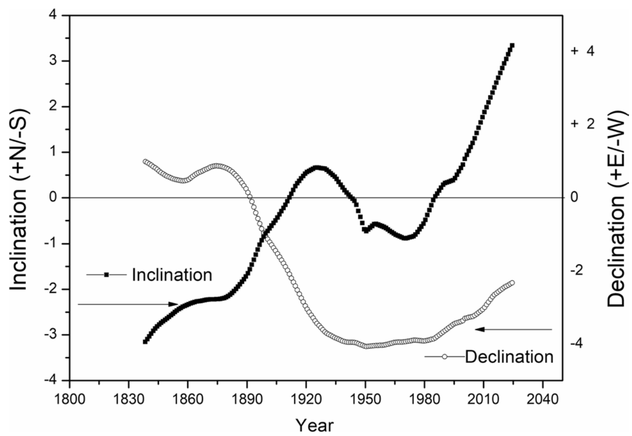

Fig. 5 Plot of Inclination and Declination from 1837 to 2024 at Thiruvananthapuram Observatory (8.51°N,77.96° E) based on the International Geomagnetic Reference Field (IGRF) model

migration of the dip zero, effectively the magnetic equator on the western coast, towards the south was ~ 1.9 km/year from 1837 to 1859. Between the period of 1868 and 1917, the magnetic dip at Thiruvananthapuram is recorded to be steady, indicating that it may have been a period when the magnetic equator remained stationary. This observation is complemented to some extent by the International Geomagnetic Reference Field (IGRF) model for the geographical coordinates of Thiruvananthapuram, which shows that the inclination (dip) remained constant from 1865 to 1890, as shown in Fig. 5. According to the model, the dip at Thiruvananthapuram was zero for the year 1911.

In contrast, the records at the TVPM observatory show that dip zero was measured in the year 1921 at TVPM. A closer look at the IGRF model also shows that the magnetic dip breached the zero dip value three times in history between 1890 and 1990. During the first instance of zero dip breach, it showed a southern migration for the period 1912–1926. For the next breach, it followed a northern migration from 1927 to 1965, and for the third breach, a southern migration beyond 1965 is modelled.

The recording of magnetic dip zero at TVPM in 1921 by the TVPM observatory provides ground-based evidence for the southern migration of the magnetic dip zero along the western coast up to the 8° 30′ N latitude. The credit for this vital finding is due to Dr K. R. Ramanathan, who was the Director of the Observatory during this period. The absence of magnetic measurements along the eastern coast remains a scientific vacuum in the history of the Observatory. The magnetic measurements made by the TVPM observatory from 1838 to 1920 over 82 years proved that the zero of the magnetic dip on the western coast of India had migrated southward at a rate of ~ 2.6 km/year from the latitude ~ 9° 57′ N to the latitude ~ 8° 30′ N, a difference of ~ 1° 27′ in latitude and that the migration along the longitude was from ~ 76° 16′ E to ~ 76° 59′ E a difference of ~ 0° 43′ in longitude. Examining the historical data from 1921 to 1941 for the magnetic dip measured at the TVPM observatory reveals a magnetic reversal, as shown in Fig. 3. The 1971 magnetic survey showed that the magnetic equator was located ~ 65 km north of the TVPM observatory. It confirmed that a northward migration of the magnetic dip zero had occurred along the western coast of India after 1921. The 1981 magnetic survey revealed that the magnetic dip zero was located south of TVPM, confirming the reversal of the migration of the magnetic dip equator from a northward direction to a southward direction. IIG, which conducted a study in 2010 using data from the Trivandrum Magnetic Observatory up to 1999 and data from other magnetic observatories across India, confirmed the continuation of the southern migration of the dip equator after the epoch of 1971. The IGRF model complements these ground-based measurements.

Reading through the history of the Travancore observatory from 1836 to 1999, one is mesmerized by how an institution envisioned for astronomy was partitioned and contributed to geomagnetism on such a grand scale. Forgotten in time, the contributions of the Travancore Observatory span the first ground-based mapping of the magnetic equator in India in 1839, the first ground-based record for the southern migration of the dip equator on the west coast of India in 1859, and the first ground-based evidence for the northward migration of the magnetic dip equator in South India. The training provided and the hourly data collected at the Travancore observatory resulted in the birth of two iconic institutions that have flourished in their mandates for Meteorology and Geomagnetism, respectively. No scientific production on the geomagnetism and migration of the magnetic equator in India could claim to be complete without citing the Travancore Observatory's 162 years of contributions to this science.

Acknowledgements The authors would like to thank the anonymous reviewers for their constructive comments.

Author contributions Jayakrishnan- Conceptualization, Methodology, Fund acquisition, Supervision, Data collection, writing draft, editing. Fazil- Data collection. Rahul- Data collection.

Funding The authors would like to thank INSA, New Delhi for funding this research work under grant No. HS/RC/233 dated July 4 2024.

Data availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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