NOTES AND RECORDS

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THE INSTRUMENTS OF EXPEDITIONARY SCIENCE AND THE REWORKING OF NINETEENTH-CENTURY MAGNETIC EXPERIMENT

by

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During the mid-nineteenth century, British naval expeditions navigated the world as part of the most extensive scientific undertaking of the age. Between 1839 and the early 1850s, the British government orchestrated a global surveying of the Earth's magnetic phenomena: this was a philosophical enterprise of unprecedented state support and geographical extent. But to conduct this investigation relied on the use of immensely delicate instruments, known as 'dipping needles'. The most celebrated of these were those of Robert Were Fox, designed and built in Cornwall. Yet these devices were difficult to physically maintain and ensuring accuracy throughout a magnetic experiment was challenging. In 2020, Crosbie Smith and I took an original Fox dipping needle on a voyage from Falmouth to Cape Town, retracing the routes of survey expeditions, including James Clark Ross's 1839–43 Antarctic venture. The article offers an account of our experiences, combined with historical reports of the instrument's past performances. It explores the instrumental challenges involved in nineteenth-century global experimental investigation. The great problem for the British magnetic survey was of coordinating standardized experimental measurements over vast expanses of space and time. As this article argues, this was very much a question of instrumental management, both of dipping needles and of human performers.

Keywords: terrestrial magnetism, survey science, experiment, Magnetic Crusade, navy, standardization

INTRODUCTION

During the mid-nineteenth century, British naval expeditions navigated the world as part of the most extensive scientific undertaking of the age. With government support, the British Magnetic Scheme (BMS), later known as the 'Magnetic Crusade', sought to survey the Earth's magnetic phenomena.[1] As a very early example of a state-sponsored global

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[1] On this term and the BMS, see Matthew Goodman, 'From "magnetic fever" to "magnetical insanity": historical geographies of British terrestrial magnetic research, 1833–1857', PhD thesis, University of Glasgow (2018), pp. 16–17; John Cawood, 'The Magnetic

empirical enquiry, we might recognize in the BMS the fundamental elements of the sort of 'big science' that has, since World War II, come to shape expert advice and political policy, especially at moments of environmental catastrophe and global pandemic.[2] This is not to say that the BMS was the first state project of this nature; Captain James Cook's voyages of scientific discovery between 1768 and 1779, for instance, unified the ambitions and resources of the Royal Navy and Royal Society, while the government's Board of Longitude worked to resolve and regulate problems of oceanic navigation between its inauguration in 1714 and its termination in 1828. In both cases, it was the Admiralty that delivered the organizing direction and material resources to fulfil the state's scientific policies. Nevertheless, the BMS undoubtedly marked a significant expansion in this government culture of natural inquiry and it was the navy, again, that was crucial to realizing these philosophical aspirations. The challenge for the BMS was to ensure that a varied range of observers employed standardized experimental techniques and apparatus, over extended periods of time and vast geographical space, to produce a highly disciplined and consistent body of magnetic data from which a true knowledge of the Earth's magnetic properties could be obtained. This was a philosophical enterprise of unprecedented state investment and geographical extent, but it relied on the use of immensely delicate instruments, known as 'dipping needles', the most celebrated of which were those of Robert Were Fox (1789–1877). Famously, it was with a Fox type that captain James Clark Ross (1800–1863) first calculated the South Magnetic Pole's location in 1841, contributing to the device's reputation for reliability. Yet behind the instrument's public image, its users often struggled to manage their Fox types during the months and years of oceanic travel that expeditionary survey work involved: they were easily damaged and it was often difficult to maintain their accuracy. As recent historical studies of the BMS have shown, evaluating the performance of its instruments is crucial to our understanding of the enterprise's effectiveness and ability to secure credibility for its findings.[3] At stake here was the question of how to regulate global experimental observations in the mid-nineteenth century.

In the summer of 2019, local historians Henrietta Boex, Michael Carver and Louise Spencer located a working Fox-type dipping needle in the possession of the Royal Cornwall Polytechnic Society (RCPS), at Falmouth. The following year, I took this instrument on a voyage from Bristol to Cape Town, retracing the routes of several BMS expeditions, notably Ross's 1839–43 Antarctic venture, and performing experimental magnetic experiments along the way. In this work, I was ably assisted by Professor Crosbie Smith, who agreed to become my subordinate for the duration of the trip: he understood the importance of acting on instruction during experiments and recognized that any dissent could undermine the disciplined collection of magnetic data.[4] Through this

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Crusade: science and politics in early Victorian Britain', *Isis* **70**, 493–518; Christopher Carter, *Magnetic fever: global imperialism and empiricism in the nineteenth century* (American Philosophical Society, Philadelphia, 2009).

[2] The term 'big science' is usually associated with Alvin Weinberg's discussion of the relationship between the 'military–industrial complex' and the United States' financing of scientific and technological research. See Alvin M. Weinberg, 'Impact of large-scale science on the United States', *Science* **134**, 161–164 (1961).

[3] Matthew Goodman, 'Proving instruments credible in the early nineteenth century: the British magnetic survey and site-specific experimentation', *Notes Rec. R. Soc.* **70**, 251–268 (2016); Anita McConnell, 'Surveying terrestrial magnetism in time and space', *Archs Nat. Hist.* **32**, 346–360 (2005); Trevor H. Levere, 'Magnetic instruments in the Canadian Arctic expeditions of Franklin, Lefroy, and Nares', *Ann. Sci.* **43**, 57–76 (1986).

[4] Thanks to Tommy Grimshaw for discussions over the management of laboratory assistants.

endeavour, we hoped to acquire unique experiences of the instruments that underpinned the BMS's inquiry. From a personal perspective, aside from the constant pursuit of adventure, I wanted to undertake this voyage to get a sense of how difficult it was for past users of Fox's dipping needles to become accomplished magnetic experimentalists. Part of my current research into the Fox needle's place within the government's magnetic enterprise considers the usability of these devices. However, the surviving historical documentation, while valuable, delivers a limited conception of why these instruments secured the reputation that they did and the ways in which users came to appreciate, or struggle with, their Fox types. Being a historian, as opposed to a scientist, I felt that actual experimental experience and a tacit, tactile knowledge of Fox's dipping needles, would enhance the authority of my historical account of the BMS. At the same time, I was excited to discover what sort of impact the reworking of historic experimental inquiries would have on my written account of this global scientific undertaking.

This paper is an account of our historic re-enactments and argues that such hands-on experience has important implications for our understanding of a scheme that effectively offered a model framework of how to orchestrate global scientific enterprise, or what Simon Naylor and Simon Schaffer have described as the 'survey sciences'.[5] Combining our own experiences with historical reports of the instrument's performance, this investigation explores the challenges of global magnetic investigation and delivers insights on the importance of user experience, the value of contemporary instruction manuals, the risks of technological overconfidence, and the threats of compromised accuracy and localized interference. As this article argues, the coordinated collection of magnetic data was very much a question of instrumental management, both of dipping needles and of human performers. This crucial moment in the formation of state–science relations was contingent on the intelligibility of written direction, instrumental integrity, and user familiarity and confidence.

Considering the value and limitations of experimental reconstruction for historians of science, my study of Fox's dipping needle contributes to a growing literature on the potential of these methods for enhancing our understanding of past scientific practices. Though common in disciplines such as archaeology, musicology and art history, reconstruction in the history and philosophy of science has been controversial, especially as replicating what 'really' happened in an experiment risks a positivistic line of analysis.[6] At the same time, reconstructed experiments are limited in that, as historians, we have preconceptions of what results to expect, while it is impossible to replicate the physical and cultural contexts, or the thoughts and experiences of historic actors, in our own experimental labour. In many respects, the problem here is one of terminology. While musicologists and anthropologists are happy to define performative work as 'replication', and art historians and museum conservationists might favour 'reconstruction' or 're-enactment', historian Otto Sibum has rejected such terms on the grounds that we cannot re-enact or reconstruct past experiments, each performance being unique.[7] Likewise, to

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[5] Simon Naylor and Simon Schaffer, 'Nineteenth-century survey sciences: enterprises, expeditions and exhibitions: introduction', *Notes Rec. R. Soc.* **73**, 135–147 (2019).

[6] Hjalmar Fors, Lawrence M. Principe and H. Otto Sibum, 'From the library to the laboratory and back again: experiment as a tool for historians of science', *Ambix* **63**, 85–97 (2016), at p. 88; on these techniques in different disciplines see Sven Dupré, Anna Harris, Julia Kursell, Patricia Lulof and Maartje Stols-Witlox (eds), 'Introduction', in *Reconstruction, replication and re-enactment in the humanities and social sciences* (Amsterdam University Press, Amsterdam, 2020), pp. 9–34.

[7] Dupré *et al.*, *op. cit.* (note 6), pp. 10 and 25; for a 'replication' of Faraday's 1821 electro-magnetic rotation experiment, see Dietmar Höttecke, 'How and what can we learn from replicating historical experiments? A case study', *Sci. Educn* **9**, 343–362 (2000).

‘replicate’ implies that such historical investigation is attempting to verify or check past results, which would be the work of a scientist, rather than a producer of historical information. Together with Hjalmar Fors and Lawrence Principe, Sibum instead favoured the terms ‘reworking’ and ‘reproduction’, which emphasize that it is the experimental process, rather than the end result, that is under scrutiny.[8] This terminological distinction seems fair, but in this paper, the terms ‘refashioning’ and ‘re-enactment’ are also acceptable, given that to experiment with the dipping needle was often a performance not too far removed from acting. As historians, when we rework historic experiments, we are also performing a character study of historical actors, endeavouring to conceive of, acquire and follow their techniques.

Through such analysis, experiencing past epistemological practices offers rich insights into the actual materials of historic experiment, helping us to think about the ways in which past scientific practitioners engaged with the processes and physical objects of their investigations. Naturally, we should approach these non-textual resources with the same rigour with which we assess written documentation.[9] Yet in combination with written materials, experiences of historic experiments can enhance our perception of our actors’ own encounters, including the sights, smells, sounds, feel and tastes of scientific activity, as well as their thought processes. Such sensual understanding is often hard to obtain from documentation and falls within what is widely termed ‘tacit knowledge’, or what Sibum has called ‘gestural knowledge’, this being the accumulation of working know-how and an appreciation for the practical, tactile skills involved in past scientific inquiry. This can help us resolve ambiguities within written accounts of experiments and fill in the gaps arising from the purely textual: it is often difficult, from documentation, to accurately visualize how historic experimental arrangements looked, and this matters to our conception of how past philosophical inquiry was organized.[10] Similarly, the reasons for some experimental courses and actions, which might not have been recorded, or which seem vague to us today, can become apparent through practical experiences: skills and assumptions that historical actors have not thought worth recording were frequently crucial to the performance of their scientific work.[11] Reworking experiment, such as Sibum’s now classic study of James Joule’s paddle-wheel trials to determine a mechanical value of heat, enhances our understanding of the unrecorded elements within scientific work on which past philosophical claims rested.[12] Furthermore, these methodological techniques can help to unpack the relationship between experimenter and scientific instrument. As Peter Heering has observed, instruments have ambiguous roles in experiment, apparently lacking

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[8] Fors *et al.*, *op. cit.* (note 6), pp. 93–94.

[9] *Ibid.*, p. 85.

[10] *Ibid.*, pp. 90–91.

[11] Heinz Otto Sibum, ‘Reworking the mechanical value of heat: instruments of precision and gestures of accuracy in early Victorian England’, *Stud. Hist. Phil. Sci.* **26**, 73–106 (1995), at pp. 76 and 85.

[12] Although the reworking of historic experiments as an historiographical tool dates back to the 1960s, particularly in histories of physics and alchemy, it was Sibum’s performance of James Joule’s paddle-wheel experiment to determine a mechanical value of heat, published in 1995, that first demonstrated the analytical potential of this methodology. Sibum found that Joule’s practices of measuring temperature increases arising from the continual movement of a paddle-wheel through water depended on a range of skills and techniques, unrecorded in Joule’s published accounts of the experiment. Along with the physical demands of winding up the heavy weights, carefully timed thermometer measurements, and challenges in regulating room temperature, Sibum determined that Joule’s experimental process relied on thermometrical skills that were common in Britain’s brewing industry and which he obtained through his father’s beer-making business. These experiences equipped Joule with the ‘gestural knowledge’—the practical know-how—to obtain his experimental results. Argued in Sibum, *op. cit.* (note 11).

agency but, at other times, shaping the manner in which an experimenter performs investigations. Instruments are designed to function in a certain way and yet are subject to an actor's decision over how to mobilize them. The use of experimental devices therefore represents a complex interaction between conditioning experimental practices and the varying intentions of the users.[13] For our dipping needle trials, we endeavoured to follow the instructions laid out in Fox's correspondence, as well as in guiding manuals published for naval and military officers, while our actions would also be shaped by the apparatus itself. Yet a key question for our inquiry was to ascertain the extent to which written guidance and the instrument's physical properties conspired to standardize magnetic experiments, and to assess the degree to which we could exert agency over our measurements.

Our investigation therefore set out to examine three questions for which reworking magnetic experiments would provide non-textual evidence of the Fox type's performance. Primarily, what skills and gestural, tacit knowledge were required to perform nineteenth-century magnetic experiments and how significant was the role of experience in handling these delicate survey instruments? Secondly, how reliable were Fox types and what were the threats to the production of accurate magnetic data, in terms of instrumental failings, human fallibilities, and the capriciousness of expeditionary scientific activity? And, finally, what was the relationship between these magnetic devices and their users? By obtaining practical experience of these concerns through the reworking of magnetic experiments, this article examines the difficulties that promoters of magnetic science faced in orchestrating global scientific investigation in the mid-nineteenth century. To conduct what was an unprecedented experimental measurement of a natural phenomenon over immense geographical space involved highly standardized instruments and disciplined experimental practices to regulate the production of empirical data. But it also entailed the cultivation of a network of skilled experimentalists possessing growing experience of terrestrial magnetism and the devices with which it could be measured. Through such analysis, this article provides a study of the complex relationship between experimentalist and experimental instrument on which the credibility of the great state-supported scientific endeavour of the age depended.

The Fox type

Following Napoléon Bonaparte's defeat in 1815, the Royal Navy found itself short of an obvious role in what was the first period of sustained peace between Britain and France for over two decades. Yet the previous twenty years had seen the Admiralty emerge as a vastly powerful organ of the state, richly financed and with a strong bureaucratic culture, capable of delivering effective administration and clearly directed policy.[14] Beyond policing the coasts and trade links of Britain's expanding collection of overseas territories, the Admiralty's attention turned to locating the North West Passage, uniting the Atlantic and Pacific through the Arctic waters of northern America. In 1818, the navy launched the

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[13] Peter Heering, 'An experimenter's gotta do what an experimenter's gotta do—but how?', *Isis* **101**, 794–805 (2010).

[14] For studies of the Royal Navy's organization and bureaucratic culture, see Roger Morriss, *The foundations of British maritime ascendancy: resources, logistics and the state, 1755–1815* (Cambridge University Press, Cambridge, 2011), pp. 4–5; C. I. Hamilton, *The making of the modern Admiralty: British naval policy-making, 1805–1927* (Cambridge University Press, Cambridge, 2011); Roger Morriss, *Naval power and British culture, 1760–1850: public trust and government ideology* (Routledge, London, 2017).

first of a series of expeditions in search of this potentially profitable route. During these voyages, throughout the 1820s and 1830s, a network of naval and military officers became increasingly aware of how erratically the Earth's magnetic properties varied over time and space, especially in polar regions, where navigation by compass was so difficult. Individuals such as John Franklin, Edward Sabine, Henry Foster and William Edward Parry combined expeditionary duties with philosophical inquiry, publishing a host of scientific papers on a diverse range of natural phenomena, including those magnetical.[15] In 1831, this growing interest in the polar sciences culminated with James Clark Ross's locating of the North Magnetic Pole. Despite this, when it came to the science of terrestrial magnetism, Britain lagged behind its Continental rivals. In early nineteenth-century Paris, Alexander von Humboldt (1769–1859) had collected magnetic data from all over Europe in order to add weight to his 'cosmical' vision of nature in which all natural phenomena were united. Then, in 1834, Carl Gauss (1777–1855) and Wilhelm Weber (1804–1891) surpassed Humboldt's efforts by establishing a far more extensive international system of magnetic inquiry, the Göttingen Magnetische Verein. Gauss and Weber envisaged this as a world-wide investigation, conducted with standardized instruments, regulated observations, and synchronized magnetic measurements.[16]

Determined to contribute to, and surpass, this scientific enterprise, an influential group of British scientific authorities combined philosophical ambition with concerns over accurate navigation to persuade their government to initiate a survey of the Earth's magnetic properties. With Sabine's organization and John Herschel's endorsement, this magnetic lobby campaigned for the launch of a naval expedition to the Antarctic, tasked with locating the South Magnetic Pole and charting the magnetism of the southern polar seas, and the establishment of four overseas observatories to measure magnetic phenomena in fixed positions over time. In late 1838, this campaign finally secured government support.[17] A year later, in September 1839, Ross took command of HMS *Terror* and *Erebus* and commenced a four-year expedition to the Antarctic. Ross and *Terror's* captain, Francis Crozier, performed magnetic experiments as they sailed down the Atlantic and across the Indian Ocean, setting up magnetic observatories at St Helena, Cape Town and Hobart. These would, initially, be sites of scientific activity quite distinct from existing colonial astronomical observatories but, within a few years, the Cape's magnetic and astronomical observatories would merge together into a single research institution. Although disappointed to find that the South Magnetic Pole was far inland, Ross went on to determine its approximate location in 1841 and returned to Britain in 1843 with a wealth of magnetic data.

Ross's Antarctic expedition marked the first of the series of state-financed naval expeditions that, along with observatory measurements, constituted the BMS. In 1841, the Niger Expedition recorded magnetic phenomena along the coast of West Africa, while in 1843 captain Edward Belcher sailed for Borneo, Korea and Japan to magnetically chart the Far East aboard HMS *Samarang*. In 1845, Sabine despatched Henry Clerk of the Royal

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[15] On terrestrial magnetism and polar exploration, see Granville Allen Mawer, *South by northwest: the magnetic crusade and the contest for Antarctica* (Birlinn, Edinburgh, 2006); McConnell, *op. cit.* (note 3).

[16] James Gabriel O'Hara, 'Gauss and the Royal Society: the reception of his ideas on magnetism in Britain (1832–1842)', *Notes Rec. R. Soc. Lond.* **38**, 17–78 (1983), at p. 28; John Cawood, 'Terrestrial magnetism and the development of international collaboration in the early nineteenth century', *Ann. Sci.* **34**, 551–587 (1977).

[17] J. Cawood, *op. cit.* (note 1).

Artillery aboard the barque *Pagoda* to complete Ross's Southern Hemisphere survey, and, that same year, Franklin took command of *Terror* and *Erebus* with orders to acquire new magnetic data from the Arctic. The BMS launched similar ventures to the West Indies, Australasia and North America, including Henry Lefroy's laborious overland survey of northern Canada. This culminated in Owen Stanley's circumnavigation of the globe via Australia and the Pacific aboard HMS *Rattlesnake*, between 1846 and 1850. The BMS marked a departure in scientific endeavour, in terms of both government investment and geographical extent, but the effectiveness of this enterprise was contingent on reliable scientific instruments, capable of accurately measuring magnetic phenomena.

In the nineteenth century, it was understood that to survey the Earth's magnetism required the measurement of three properties. First, there was magnetic variation, or 'declination', being the difference between magnetic north as shown by a compass and geographic north as indicated by the Pole Star. The second property was inclination, or 'dip', which was the horizontal angle given by a magnetized needle pointed towards the North Magnetic Pole. Finally, there was intensity, this being the strength of the Earth's magnetic force. For measuring these two latter quantities, specific instruments were required: dipping needles for inclination and magnetometers, consisting of a suspended magnetic needle put in motion, for intensity. The problem was that the best instruments for such measurements were constructed on the Continent and were immensely delicate. To measure dip required a magnetized needle, balanced horizontally, that oscillated in reference to the Earth's magnetic influence. Not only had this to be sensitive, but the pivots on which the needle moved had to be precisely made and carefully balanced.[18] For oceanic expeditions, such devices were poorly suited, with stormy seas and rolling waves a constant threat to the instrument's physical integrity.

It was to this instrumental challenge that Fox provided a solution. Living in the Cornish port of Falmouth, his initial philosophical inquiries concerned the escalation of temperature with depth in local mines and the structure of subterranean veins of copper and tin. Charting these mineral deposits required robust magnetic instruments that could be used within the harsh industrial setting of the mine: it was from this experimental work that Fox developed his own dipping needle, which would be well suited to expeditionary science.[19] For his instrument, Fox suspended a magnetized needle within a system of pivots and jewelled pallets: the needle's axis had extremely delicate pivots which sat in a pair of aligned jewelled holes, to allow the free oscillation of the magnetic needle (figure 1). This was housed in a circular metal box with a glass face.[20] To measure dip, the needle was vibrated with a gentle tap, then the angle of dip read off against the graduated circle of the instrument's face, on which a moveable magnifying glass could be adjusted with which to read values in degrees (°), minutes (′) and seconds (″).[21] Fox's dipping needle could also measure the Earth's magnetic intensity by the use of two three-inch steel magnets, known

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[18] Levere, *op. cit.* (note 3); Trevor H. Levere, *Science and the Canadian arctic: a century of exploration, 1818–1918* (Cambridge University Press, Cambridge, 1993), p. 152.

[19] As argued in Jenny Bulstrode, 'Men, mines, and machines: Robert Were Fox, the dip-circle and the Cornish system', Part III dissertation, History and Philosophy of Science Department, University of Cambridge (2013); see also Edward Gillin, 'Cornish science, mine experiments, and Robert Were Fox's Penjerrick letters', *Notes Rec. R. Soc.* **76**, 5–26 (2021).

[20] Fox's instrument was sometimes referred to as a 'dip circle', with the dipping needle technically being the magnetized needle itself. However, it was common to refer to the complete apparatus as a 'dipping needle'.

[21] Robert Were Fox, 'Notice of an instrument for ascertaining various properties of terrestrial magnetism, and affording a permanent standard measure of its intensity in every latitude', *Phil. Mag.* (3rd Series) **4**, 81–88 (1834), at pp. 81–82.

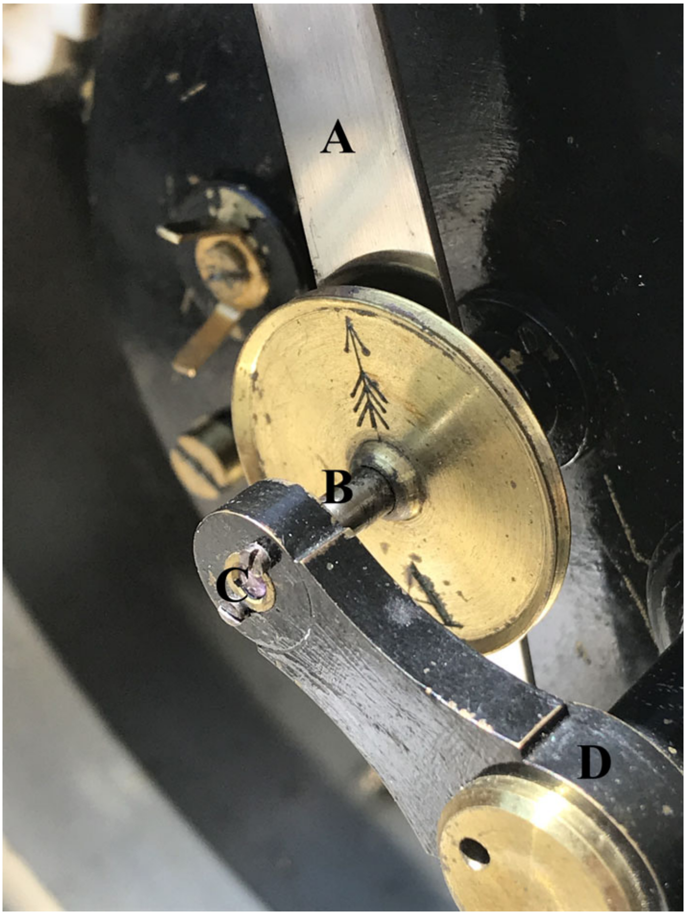

Figure 1. The magnetic needle (A) of the Royal Cornwall Polytechnic Society's Fox type, suspended by its pivots (B) between jewelled pallets. The outer jewel (C) is held within an arm, attached to an axle (D) which connects it to the circle's face. (Author's image, 2020.) (Online version in colour.)

as 'deflectors'.[22] After attaining the dip by directing the needle towards the Magnetic North Pole and recording the angles given, the dial on the circle's rear could be lined up to correspond with the angle of dip, before the deflectors were screwed into the back of the instrument. This magnetic impulse repelled the needle and, by adjusting a movable disc around the rear of the device, could be applied at a regular angle of 30° from the dip initially indicated, so as to ensure that the position of this influence was consistent.[23] The difference in degrees between dip and deflection provided measures of intensity. At this point, for a more accurate experimental result, weights could be used to weigh the Earth's magnetic intensity. By opening the circle's glass cover, a silk thread was looped around the needle's grooved wheel and hooks attached to the thread. Weights would then be added to coerce the needle from its angle of deflection back to its angle of dip. With the

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[22] *Ibid*., p. 83.

[23] Robert Were Fox, *Description of R. W. Fox's dipping needle deflector* (Jane Trathan, Falmouth, *ca* 1835), p. 6.

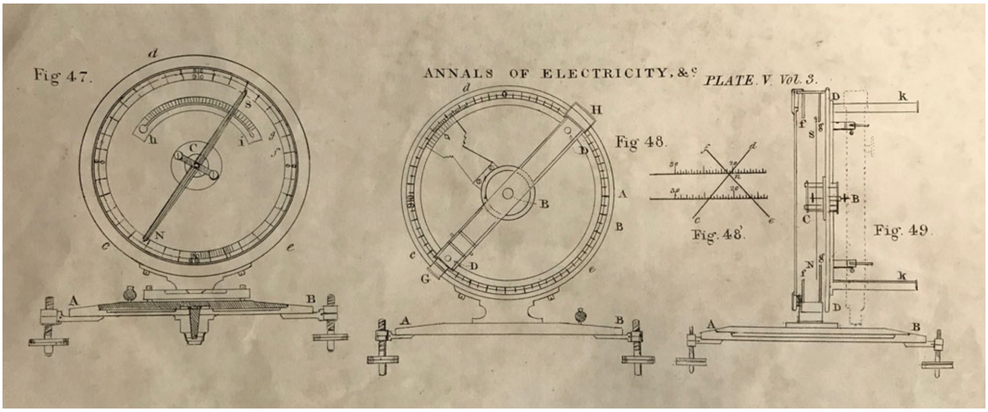

Figure 2. Fox's depiction of his dipping needle, as published in *The Annals of electricity* (Sherwood, Gilbert, and Piper, London, 1839; reproduced with permission). (Online version in colour.)

deflecting magnets giving a constant magnetic force, the weight required to induce the needle back to its original dip indicated the strength of the Earth's magnetic force. A greater intensity would diminish the relative impact of the deflectors such that it would take greater weight to return the needle to its indicated dip.[24] Relative intensity could then be calculated in reference to a single fixed site that was initially measured and used as an index, usually at London or Falmouth.

Fox's dipping needle was little known beyond Cornwall until, in 1834, he published an account of the device in the *Philosophical Magazine* (figure 2).[25] This caught the attention of John Franklin, who, in October, travelled to Falmouth to inspect the instrument for himself at Fox's home.[26] Impressed, Franklin promoted Fox's device with influential individuals at the Admiralty, including Ross and Francis Beaufort, the Hydrographer of the Navy.[27] At the same time, Fox built credibility for his instrument with leading scientific authorities, notably Edward Sabine and Humphrey Lloyd, who employed it for their ongoing magnetic survey of the British Isles.[28] When the government initiated the BMS, the Fox was well established as the navy's premier choice for magnetic survey work. By the time Ross and Crozier sailed for the Antarctic in September 1839, they possessed Fox dipping needles and it was with his instrument that, on 28 January 1841, Ross calculated the Magnetic South Pole's position. This performance elevated the Fox type to celebrity among scientific audiences and confirmed its use in subsequent naval expeditions. It is not that Fox types were the only dipping needles that the BMS issued to crews, but that they had an unrivalled reputation for measurements at sea. For onshore and observatory experiments, there was a preference for the instruments of London's Charles Robinson and Paris's Henri-Prudence Gambey, which were widely perceived to be of greater accuracy

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[24] *Ibid*., pp. 7–8.

[25] Fox, *op. cit.* (note 21), pp. 81–88.

[26] R. L. Brett (ed.), *Barclay Fox's journal* (Bell & Hyman, London, 1979), p. 71.

[27] Levere, *op. cit.* (note 18), p. 155; Andrew Lambert, *Franklin: tragic hero of polar navigation* (Faber & Faber, London, 2009), p. 83.

[28] Goodman, *op. cit.* (note 3).

than Fox's wares. The Niger Expedition, for instance, carried an assortment of dipping needles for onshore and on-board experiments: along with Fox types for days at sea and on the river, the Royal Society issued the crew with a highly delicate magnetometer that Weber had developed at Göttingen which could be used on land when the expedition was stationary for three or four days.[29] However, for the expeditions of *Samarang*, *Rattlesnake*, *Terror*, *Erebus* and *Pagoda*, in which the majority of measurements would be made at sea, Fox types were the apparatus of choice. These data substantiated the BMS's eventual philosophical claims, which Sabine published in the Royal Society's *Philosophical Transactions*, between 1840 and 1877, through fifteen instalments of his 'Contributions to terrestrial magnetism'.

To standardize magnetic experiments, Fox and the Admiralty published a series of manuals, offering instruction to naval and military officers. For our own experiments, we took the most developed of these guides, John Herschel's 1849 *Manual of scientific enquiry*, which includes not only Sabine's instructions for magnetic observations, but also a regime of daily experimental activities for expeditionary officers, including for the collection of astronomical and meteorological data. Along with charting star positions, and recording rainfall and temperature at set hours throughout day and night, magnetic measurements featured prominently in the daily routine of a naval officer's life on expedition. After taking a bearing with a compass and determining the direction of magnetic north, this guide directed an experimentalist to align the dipping needle so that it was positioned along a north–south meridian. The needle would then vibrate within its circular case, attracted to the north, oscillating in response to the Earth's magnetic dip. An ivory disc would be rubbed on a pin, attached behind the needle, to remove friction (figure 3). The angle displayed would be recorded, giving a measure of the Earth's magnetic dip. This would be 0° were the instrument at the North or South Pole, where the planet's magnetic influence is so strong as to pull the needle straight down, and around 90° around the magnetic equator, where its influence is weakest. Ideally, this process would be performed three times with the instrument's face directed towards the west, then repeated three more times facing the east, and the six results reduced to give a mean dip. This reversing of the instrument's face neutralized potential influence from imperfections in the needle's balance.[30] The next element of a complete magnetic experiment was to determine intensity. The experimentalist would insert either one, or both, magnetic deflectors, causing a deflection, and then add ½ grain weights to gradually coerce the needle back to its dip. As a general routine, Sabine advised three observations of dip, three observations with deflectors N and S to measure the angle of deflection from dip, and then both steps to be repeated with a second needle.[31] By observing the deflectors' influence and comparing it to past readings at different locations, the Earth's relative magnetic intensity could be deduced. The data provided a representation of how the Earth's magnetic qualities changed over time and space. It was this procedure, outlined in manuals and aimed at disciplining

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[29] Edward Sabine, 'Instructions for magnetic observations in Africa', *The friend of Africa: by the Society for the Extinction of the Slave Trade, and for the Civilization of Africa*, vol. I, no. 4 (John W. Parker, London, 1841), pp. 55–57.

[30] Robert Were Fox, Letter to James Clark Ross, 18 June 1839, D-J, Ms/258/569, Sabine Correspondence, vol. 2, Royal Society Library, London (RS).

[31] Edward Sabine, 'Terrestrial magnetism', in *Manual of scientific enquiry; prepared for the use of Her Majesty's Navy: and adapted for travellers in general* (ed. John F. W. Herschel), pp. 14–53 (John Murray, London, 1849), at pp. 38–42.

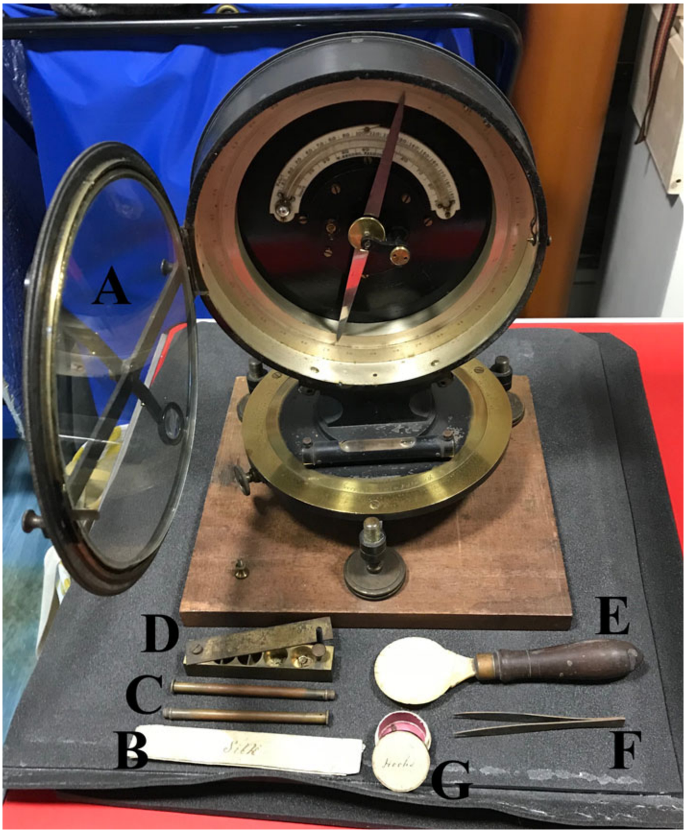

Figure 3. Fox's dipping needle and experimental apparatus. The glass cover (A) to the circle can be closed in bad weather, but still allow observations. In the foreground, clockwise from the bottom left, is a packet of silk (B), two deflectors (C), a brass tin containing various weights (D), a wooden-handled ivory disc (E), tweezers (F) for attaching weights, and a pot of 'hooks' (G) to suspend the weights from the silk. (Author's image, 2020.) (Online version in colour.)

the production of magnetic knowledge, that we attempted to implement during our reworking of this experimental enterprise.

THE VOYAGE

The RCPS's Fox type had been stored in the cellar of Falmouth Art Gallery for an unknown number of years. The history of this specific instrument is unknown, but it was in the possession of the Royal Navy's Hydrographic Office until the 1880s. Marked 'W. George. Falmouth', it is the work of Falmouth instrument maker William George. Given that before 1842, George was foreman to Thomas Jordan and that he retired on health grounds in 1845, the instrument was almost certainly constructed during this three-year period, in which he was Fox's mechanic-of-choice.[32] George's wares were, nevertheless, extremely

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[32] Robert Were Fox, Letter to Edward Sabine, 13 March 1841, BJ3/19/77-8, p. 78, Sabine Papers, The National Archives, Kew (TNA); Robert Were Fox, Letter to Edward Sabine, 3 March 1845, BJ3/19/153-4, p. 154, Sabine Papers, TNA.

similar to Jordan's earlier models, one of which is in the collections of the National Maritime Museum at Greenwich. The RCPS's Fox type is, however, in a superior working condition. Dipping needles are sensitive devices and often lose magnetic intensity over time, especially if in places of temperature variation or when subjected to regular magnetic or vibratory disturbances. Fortunately, the gallery's cellar provided a superb storage location. On inspecting the instrument, we found the magnetic needles remarkably sensitive, responding to magnets of a moderate strength positioned several metres away, and free of any rust or corrosion. To calculate how accurate the instrument was, we took it to Penjerrick Gardens, just outside Falmouth, which was one of Fox's two original dipping needle testing sites, the other being nearby Rosehill. Fox favoured these garden locations because there was little local magnetism arising from igneous rock, or iron in human constructions, or sudden temperature fluctuations. At Penjerrick on 2 November 2019, we performed six measurements of dip, giving a mean of 64° exactly, with readings varying between 63° and 65° (table 1).[33] The consistency of these results, with three taken before turning the instrument 180° to perform three more, was remarkable and, given the latitude, not unreasonable. This is not to say that this was the correct dip, but it suggested the device's consistency. Having done a practice the day before, nearby at Michael Carver's house, where we recorded a mean dip of 64° 25', the Penjerrick observations were very satisfactory.

We transported the Fox type to Bristol on 6 January 2020. Here, we took the opportunity of testing the instrument on Isambard Kingdom Brunel's SS *Great Britain* to see how the needle acted on board a nineteenth-century iron vessel. Given that the instrument's construction coincided with that of the ship, between 1839 and 1844, this made for a poignant trial. This was especially appropriate given that the *Great Britain* ran aground on the east coast of Ireland in 1846, with the disaster likely to have been the result of a navigation error arising from the ship's iron interfering with its compass. This performance of the Fox would, I speculate, add weight to this conclusion, with the *Great Britain* having a devastating magnetic influence on the dipping needle. We placed the device in several locations on deck, including at the stern near where the compass would have been positioned, and observed alarming dip readings of between 85° and 90° (figure 4). In pulling the needle straight down, the ship produced a measure that would, geographically, only be possible in polar regions. To check that the instrument had not been damaged since leaving Cornwall, we took comparative measures in the car park, far from the ship, and recorded more likely dips of between 67° and 69°. The ship's magnetic influence was clearly immense.

The following day, we boarded our vessel, the MS *Marco Polo*. Launched in 1964, this yacht-like ship represented one of the last true ocean liners (as opposed to cruise ships) in service and, with a gross tonnage of 22 080, one of the smallest passenger vessels available to us. For comparison, modern-day cruise ships tend to have a gross tonnage of between 140 000 and 230 000, with Cunard's *Queen Mary 2* a rather modest 149 215 in contrast to the *Symphony of Seas* at 228 081, the largest passenger ship at the time of our voyage. This question of size is relevant because, for our purposes, the smaller the mass of metal on which we were experimenting, the better, given the ship's potential to interfere with our instrument. At the same time, lacking the BMS's state funding and the Royal Navy's resources, this was the most favourable option to be economically viable. The

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[33] Dip is measured by degrees (°), which are divided into sixty minutes, indicated by a single dash (′), which are in turn divided into sixty seconds, indicated by a double dash (″).

Table 1. Results of dip experiments between Falmouth and East London, 2019–2021.

Location	Date	Latitude	Longitude	Temperature (°C)	Local time	Mean dip	Mean deflector measures (if performed)
Mylor Bridge, near Falmouth	1 Nov 2019	50°11′26″ N	5°4′24″ W	21	4.30 p.m.	64°25′0″	
Penjerrick, near Falmouth	2 Nov 2019	50°8′7.8″ N	5°6′29.88″ W	11	2.50 p.m.	64°0′0″	
SS *Great Britain*, Bristol	6 Jan 2020	unrecorded	unrecorded	7	1.20 p.m.	between 85° and 90°	
SS *Great Britain*, car park, Bristol	6 Jan 2020	unrecorded	unrecorded	7	2.30 p.m.	between 67° and 69°	
Lisbon, on shore	9 Jan 2020	38°42′47″ N	9°7′19″ W	19	2.45 p.m.	42°54′9″	
Lisbon, on board	9 Jan 2020	38°42′47″ N	9°7′19″ W	19	3.30 p.m.	68°33′45″	
At sea, SSE of Gran Canaria	13 Jan 2020	26°42′15″ N	15°4′47″ W	21	7.33 a.m.	54°52′3″	
Cape Verde, on board	15 Jan 2020	16°58′56″ N	24°57′9″ W	23	8.30 a.m.	50°55′33″	32°9′54″ (with ‘S’)
At sea, mid-Atlantic	17 Jan 2020	7°15′46.14″ N	19°23′34.49″ W	38	9.45 a.m.	24°30′0″	42°30′ (with ‘S’), 53°9′54″ (with ‘N’), 46°33′45″ (with both)
At sea, mid-Atlantic (Equator)	18 Jan 2020	1°47′2″ N	16°10′52″ W	32	9.45 a.m.	11°24′59″	
At sea, mid-Atlantic	20 Jan 2020	10°23′34″ S	9°4′55″ W	33	5.05 p.m.	needle too close to axle to oscillate	
St Helena, on board	21 Jan 2020	15°53′57″ S	5°38′29″ W	29	6.20 p.m.	needle too close to axle to oscillate	52°12′29.9″ (with ‘S’), 54°9′59″ (with ‘N’), 53°19′59″ (with both)
Cape Town, on board	28 Jan 2020	33°55′7″ S	18°25′23″ E	unrecorded	6.30 p.m.	19°9′59″	
East London, on shore	4 Feb 2020	33°1′28″ S	27°54′27″ E	33.5	1.00 p.m.	65°24′55″	72°9′59″ (with ‘S’)
East London, on board	4 Feb 2020	32°29′4″ S	28°47′47″ E	29	5.50 p.m.	13°49′59″	
Rosehill, Falmouth	13 Oct 2021	50°8′54″ N	5°4′10″ W	23	4.30 p.m.	65°58′19″	

Figure 4. The Fox type on board the SS *Great Britain*, with the magnetic needle pulled straight down at almost 90°, which erroneously indicated our position being close to the North Magnetic Pole. (Author's image, 2020.) (Online version in colour.)

Marco Polo was due to follow our intended route from England to Cape Town, via Cape Verde and St Helena, which was similar to Ross's course *en route* to Hobart and Antarctica between late 1839 and 1841. His journey included stops at Tenerife and Madeira before reaching St Helena, but we could find no company that was replicating this precise voyage. Overall, the *Marco Polo* was the most historically accurate option open to us. On board the ship, we identified the deck furthest astern as the most suitable for magnetic experiments. Though there was potential disturbance from the taffrail, this site aft was decked in wood and provisioned with a high wooden table to give distance between

Figure 5. A magnetic experiment underway at the stern of the *Marco Polo*. (Photo: Crosbie Smith, 2020.) (Online version in colour.)

the instrument and the ship's superstructure (figure 5). Wooden ships such as *Terror* and *Erebus* did not face this problem of a metal hull. However, the *Marco Polo* was partially rebuilt during the early 1990s, with much of the upper portions of the vessel constructed with non-magnetic aluminium. Within the limits of affordable twenty-first-century ocean travel, these conditions were the most historically realistic we could attain.

We departed Avonmouth on 7 January and made our first expeditionary observations at Lisbon, comparing on-board readings with those on shore. Expecting a reduction in dip from measures taken in Britain, the readings made ashore on the harbour gave an unlikely average of 42°18′45″, which we thought too much of a change in reference to our altered latitude. Unfortunately, these experiments were interrupted by Lisbon's port security, who were concerned by our curious actions and mysterious device. After demanding we return to our ship, we were rescued by the arrival of the harbourmaster who, understanding the purpose of our experiments, sanctioned their resumption. Back on board our ship, we replicated these trials, recording a mean dip of 68°33′45″, which was far above that taken on shore, yet probably more accurate. The cause of the erratic onshore readings was likely the high iron content within the harbour's concrete structure. Nevertheless, that the on-board dip was higher than that of Falmouth, but in a lower latitude, suggests the ship was influential on the needle. The implication of these experiments was that we would be unable to accurately measure the Earth's true magnetic properties, which was expected. However, we were now confident that we would be capable of assessing how well the instrument worked, relatively, as it travelled over space.

Leaving Lisbon on 9 January, we took our next readings at sea on 13 January, about ninety miles southeast of Gran Canaria. Ross stopped at Tenerife in 1839, but we passed this island late at night. Using the same position at the ship's stern, we took six measurements, to give a mean dip of 54°52′3″. This decline, relative to Lisbon, corresponded well to our expectations as we travelled south. As our first experiments were performed on a moving ship, mid-ocean, it was remarkable how steady the needle was on a gentle swell. At Cape Verde, on 15 January, we recorded a mean dip of 50°55′33″, again corresponding to our move southwards. At the same location on 18 November 1839, Ross and Crozier took measurements aboard *Terror* and *Erebus*, recording dips of between 33° and 35° but applying their 'S' deflectors to achieve this.[34] We therefore inserted our own 'S' deflector, giving a new dip of 32°9′54″. The difference between this and the initial dip, of about 18°, can be used to calculate relative intensity. We took our next observations on 17 January, at sea, where a mean of 24°30′0″ confirmed a definite weakening in the Earth's magnetic properties. The problem in these lower latitudes was that, as the needle neared a horizontal position of 0°, the circle's axle interrupted the needle's oscillations. At our position of 7°15′46.14″ N, I suspected that we were at, or even south of, the magnetic equator which, like the poles, moves over time. Measurements here were extremely difficult and full of uncertainty as there was little force in evidence. The following day, at 1°47′2″ N, we repeated our experiments, giving a mean dip of 11°24′59″. When we used deflector 'S', a mean of 42°30′ suggested the magnet was having an increased impact on the needle, of around 31°, compared with 18° at Cape Verde. We also took the opportunity of trialling deflector 'N' before using both deflectors together. This might seem unnecessary, but with so little terrestrial magnetism acting on the needle, delivering our own magnetic impulse allowed slight variations over time and space to be rendered more apparent.

On 20 January, we attempted our first observations in the Southern Hemisphere, some way north of St Helena. However, the needle was jammed on the axle, stuck at 0°. As all measures here were useless, we tried taking the needle out and reversing it, before replacing it with our reserve 'Needle B'. As neither of these actions made any difference, I attempted to re-magnetize 'Needle A' by stroking it in a consistent direction with a permanent magnet and then, after removing 'Needle B', reinserting this within the circle. This was a difficult process, but necessary, given that it was unclear whether our instrument's lack of response was due to an injury it had suffered, or because of our geographical location. The following day we reached St Helena, but a concatenation of misfortunes undermined our plans for onshore experiments. Bad weather prevented the launch of the *Marco Polo*'s tenders, confining us to on-board measurements, albeit near the coast. Sadly, these too were confounded owing to the needle's lack of response (figure 6). Nevertheless, like Ross, we performed experiments with deflector 'S', and then with 'N' and 'S' together. With 'S', Ross measured between 41°47′ and 42°26′, while we recorded a mean of 52° 12′29.9″. When Ross used 'N' and 'S' on the island, he recorded means of 58°18′ and 59° 56′. Our rerun of this use of both deflectors, at sea, produced a mean of 53°19′.[35] We intended to perform intensity experiments with the weights at this location, but strong winds made this impossible.

From St Helena, we crossed the Atlantic to Cape Town. Port security and concerns over the safety of the instrument beyond the harbour area made it difficult to attempt onshore observations, but just off the coast we were relieved to find that the needle had returned to life since the Equator, giving a mean dip of 19°9′59″, representing an increase in terrestrial

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[34] Edward Sabine, 'Contributions to terrestrial magnetism. No. III', *Phil. Trans. R. Soc. Lond.* **132**, 9–41 (1842), at p. 15.

[35] *Ibid*., p. 21.

Figure 6. The reverse of the circle. A dial (A) can be moved around the circumference's vernier, adjusted in reference to the dip measured to maintain a constant difference between the needle at dip and the deflectors. The deflectors are screwed into holes. In this image, deflector 'S' (B) has been inserted, while the hole for deflector 'N' (C) is open. (Author's image, 2020.) (Online version in colour.)

magnetic force as we neared the South Magnetic Pole. Unfortunately, bad light, salt spray, and a rolling sea limited our experimental observations to just three and compromised the accuracy of this series. While our voyage was essentially complete, we were still keen to try the weights in an intensity experiment. At sea, we failed to acquire the skill to attach the tiny weights to the delicate hooks. However, on reaching the quiet port of East London, and encountering a complete absence of wind, with warm, dry conditions, we disembarked and performed intensity experiments on the harbour-side. These attracted a crowd of dockers and great enthusiasm from the port's security workers, who seemed to enjoy the spectacle the instrument presented. Less welcome was the large number of ants we encountered on the site of our experiments. We took initial dip readings, providing a mean of 65°24′55″. This value was arbitrary and far too high to be reliable, owing to the high proportion of iron in the surrounding vicinity, particularly in the harbour's structure and a dense network of

Figure 7. The performance of an intensity experiment with weights (A), underway at East London, with silk thread (B) wound around the grooved wheel (C) that is fixed to the needle (D). This thread suspends two hooks (E) to which weights are added with tweezers (F), so as to coerce the needle back to its dip. (Author's image, 2020.) (Online version in colour.)

nearby railway lines. However, our purpose here was to trial the weights. After recording the dip, we inserted deflector 'S', which deflected the needle to 72°9′59″. Next, we affixed a thread around the needle's grooved wheel, suspending hooks to which the tiny weights were added to coerce the needle from its deflected dip, back to 65°24′55″. Adding the weights gradually, it took a total of a fifth of a grain to restore the original measure, though it was hard to be precise owing to the thread's tendency to slip within the grooved wheel (figure 7). To confirm the high influence of the harbour's local iron, we took dip measurements back on the ship, giving a mean of 13°49′5″, which was more consistent with readings taken at Cape Town.

On leaving South Africa for England, via Suez, we packed the instrument away. On 20 March, in the Bay of Biscay, we inspected the instrument in the hope of a final set of experiments. However, the previous months of travel had, through the needle's constant tapping on the circle's axle, demagnetized the device. Its movements were now very sluggish. Then, on passing the Isles of Scilly the following day, rough weather caused the needle to tap so violently on this axle as to render it completely inert. This final incident delivered a lesson on how contingent the instrument's fitness was on good weather and calm seas, and the extent to which we had been fortunate to have such a calm passage around Africa. To correct this injury, on arriving home, I removed the needle and stroked it with a permanent magnet, effectively re-magnetizing it. Our intention was to finish this investigation by returning the instrument to Falmouth for measurements at Penjerrick, offering an idea of how its magnetic properties had changed during the expedition. However, owing to the outbreak of COVID-19, we were unable to do this until October 2021. On doing so, we employed the second of Fox's test locations, Rosehill, where we performed a final series of experiments at a location suitably near to those made at Penjerrick back in November 2019. The result of these was a mean of 65°58′19″. It must be noted that these were performed indoors, which might account for this variation from Penjerrick's mean of 64°. However, since those initial experiments two years previously the instrument had circumnavigated Africa, so a difference of just 1°58′19″ represented an extraordinary level of consistency, especially given the Earth's constantly changing magnetic properties.

Experiment and experience: assessing the Fox type

Our reworking of nineteenth-century magnetic experiments was riddled with sources of inaccuracy and uncertainty. Yet these experiences are undoubtedly of historical value to our understanding of nineteenth-century science. Despite our time with the dipping needle emphasizing the extraordinary difficulties of conducting a philosophical investigation into a natural phenomenon on a global scale during the nineteenth century, it also revealed the considerable sophistication and robustness of Fox's apparatus. This really matters to our conception of the BMS, because the entire enterprise's success and claims to accuracy were completely contingent on the reliability of its instruments. As this was the first truly world-wide, state-financed scientific inquiry, offering a model for similar investigations into a diverse range of natural phenomena—including those meteorological and astronomical—the assessment of the instrument's performance matters in how we account for the venture's credibility and attainment of kudos.[36] Predictably, the challenges to such enterprise included localized disturbing elements—especially rain, wind, and salt spray—that made the use of the weights impossible, and rough seas and bad light preventing the precise reading of the vernier. Human and natural elements presented further problems, which, while different from those encountered in the nineteenth century, highlight the fragile business of survey science. Just as we had a standoff with Lisbon's port authorities and feared taking the device ashore at Cape Town, nineteenth-century magnetic experimentalists struggled with potentially hostile local populations. One challenge that nineteenth-century crews did not face was the rapid closure of ports in response to the global pandemic of COVID-19, but such medical threats were no less prevalent in the 1840s, as the Niger Expedition found, which abandoned its magnetic inquiries following

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[36] The BMS's framework was influential for later astronomical work, as shown in Jessica Ratcliff, *The transit of Venus enterprise in Victorian Britain* (Pickering & Chatto, London, 2008).

outbreaks of malaria and yellow fever. Likewise, witnessing the shutdown of the world's centres of maritime trade and collapse of the global economy amid our own efforts to complete our scientific enterprise resonated with nineteenth-century concerns over the compatibility of free trade and quarantine implementation. During the nineteenth century, Britain established what was, effectively, the first truly world economy and, as Mark Harrison has shown, the construction of an effective sanitary regime to manage this presented an enormous challenge.[37] So for us to witness the formation of a new system of quarantine within the space of a few days emphasized the fragility of both nineteenth-century, and modern, globalization. Performing magnetic survey work in 2020 was very different from conducting similar experimental inquiries in the 1840s, but our encounters certainly echoed the experiences of nineteenth-century naval officers seeking to obtain magnetic data.

What then of the needle's performance? At the start of the voyage it had been my intention to perform as many onshore experiments as possible to accompany those taken at sea. With time, however, I abandoned this plan and kept to on-board measurements owing to the erratic and uncontrollable nature of land-based experiments. We encountered an early indication of this on the *Great Britain*, but it was the Lisbon observations that confirmed the devastating influence of local iron and steel on the needle. The problem was that our land stops were at ports, built of concrete and with large amounts of metal in their superstructure, and surrounded by iron and steel buildings, cranes and railway tracks. Our sea trials might not have produced completely accurate data, but they did provide a constant experimental location and, with time, the *Marco Polo* became a trusted site of observation: in short, we developed an understanding of how the needle should behave when in position at our ship's stern. This preference for on-board experiments resonated with those that historic users of Fox's instruments expressed. In 1840, it had been Ross's intention to make regular instrumental checks whenever opportunities for onshore experiments arose to calculate error arising from the iron of *Terror* and *Erebus*. However, St Helena's magnetic rock made it difficult to perform these tests. The igneous character of the island persuaded the captain 'that no observations on shore can be depended on under any, even the most favourable circumstances & that eventually all absolute magnetic observations must be made at sea'. In contrast to St Helena, Ross's experimental experiences on *Erebus* convinced him that on a 'ship you can do away with most of the causes of disturbance & even determine the exact value of the rest. On shore all is uncertainty & beyond the reach of determination'.[38] Though they potentially produced some magnetic interference, *Terror* and *Erebus* were experimental spaces over which Ross and Crozier exerted significant control. The same was true during the *Rattlesnake* expedition (figure 8). After Madeira and Cape Town, it was Lieutenant Joseph Dayman's preference to use a Robinson type onshore and his Fox at sea. But by April 1848, along Australia's north coast, off Cape York, he performed further comparisons between the Robinson and Fox apparatuses, finding that Robinson needle 'A1' read 33°10′2″ compared with Fox needle C's 33°8′4″. At Port Essington, Dayman compared a Fox needle on *Rattlesnake* with the same device on land, giving respective readings of 35°14′6″ and 33°48′. The error was not, he reported,

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[37] Mark Harrison, *Contagion: how commerce has spread disease* (Yale University Press, New Haven, 2012), pp. 80–82.

[38] James Clark Ross, 'Letter to Major Sabine from Capt Jms Clark Ross, HMS Erebus off C Verd', 10 November 1839, Add.9942/26, Cambridge University Library, Cambridge (CUL).

Figure 8. Owen Stanley's depiction of Dayman performing a magnetic experiment with a Fox type on Madeira, as part of the *Rattlesnake* expedition. (State Library of New South Wales, SAFE/PXC 281.) (Online version in colour.)

due to the ship's iron, but to local interference, asserting that the 'observations on board the ship at this station are the nearest to the truth, there being much iron-stone strewed over the country about the observation spot on shore'.[39] Clearly, nineteenth-century expeditions did not have to contend with the disturbing magnetic influence of modern harbour installations, but the potential of a ship to provide a controlled magnetic environment was something that appealed both to nineteenth- and to twenty-first-century experimentalists.

Along with localized magnetic disturbances, weather conditions presented a constant challenge to the range of experiments we could perform. Surprisingly, the roll of the ship did not present any difficulties to dip observations—the knack of reading the needle's angle using the vernier at moments in which the ship was in equilibrium was easy to acquire. Even with swell, there are moments in which the ship steadies and the skill of coordinating dip measurements with these lulls is soon developed and improves with time. This growing confidence in our Fox was something that Ross also experienced. When he departed England in September 1839, Ross took Fox's latest dipping circle, but struggled to master this instrument between Britain, Madeira and Tenerife.[40] At Cape Verde, however, he despatched an account of the expedition's Fox types that revealed how the two captains were growing increasingly familiar with their devices. 'Our Fox is doing now

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[39] Joseph Dayman, 'Observations of the mean magnetic inclination made on shore in the voyage of H.M.S. Rattlesnake, by Lieut. Joseph Dayman, R.N. Instruments employed: Robinson's 6-inch Inclinometer; Fox's Dipping Apparatus', in *Narrative of the voyage of H.M.S. Rattlesnake, commanded by the late Captain Owen Stanley, R.N., F.R.S. &c. during the years 1846–1850. Including discoveries and surveys in New Guinea, the Louisiade Archipelago, etc. To which is added the account of Mr. E. B. Kennedy's expedition of the Cape York Peninsula*, 2 vols (ed. John MacGillivray), vol. I, pp. 337–342 (T. & W. Boone, London, 1852), at pp. 339–340.

[40] Robert Were Fox, Letter to Edward Sabine, 5 October 1841, BJ3/19/99-100, p. 100, Sabine Papers, TNA.

most admirably in both ships', Ross reported, but confessed that he had found the dipping needle difficult to use in the expedition's earlier stages. He took responsibility for these troubles, admitting that 'much of the abuse I heaped upon him [the Fox type] the early part of the voyage properly belongs to myself for the stupidity of not doing him justice and getting a proper table made'.[41] Instrumental confidence took time to cultivate.

Nevertheless, salt spray and rain frequently prevented experiments, given that we wanted to protect the instrument from rust. Extreme heat, such as encountered around the Equator, caused its travelling box to sweat and warp, which deterred us from keeping the instrument in the sun for too long, given the importance of this wooden container for preserving the dipping needle's integrity throughout the expedition. The biggest difficulty, however, was wind. Even when slight, this prevented us from performing any on-board measurements with the weights and silk: there were few windless days at sea and, even in calm equatorial waters, the ship's motion caused a passage of air to disturb the silk. This was a problem we never resolved, and I would suggest that the only way in which nineteenth-century users of the instrument could perform such measurements would be by bringing their ships to anchor on a calm day, or by identifying a very sheltered experimental on-board location. Historical documentation supports this conclusion, with Owen Stanley writing from *Rattlesnake* in 1847 that, owing to heavy weather, his Fox type had at times been unmanageable, making measurements for 'both Dip and Intensity with weights & deflectors' impossible.[42]

We never tried the instrument in colder conditions, but this too would have been difficult. While in the Arctic aboard *Terror* in 1836, Stanley struggled with his Fox type, explaining that 'the dipping needle gave me the most trouble the weights used in ascertaining the intensity being so small & delicate as not to be easily handled with cold fingers'.[43] Even the most skilled magnetic experimentalists evidently required considerable time to become familiar with the use of weights. Stanley was not alone in finding that intensity experiments took time to perfect. Anchored off Hong Kong in 1847, Belcher reported that although he had not lost any weights, he had had to replace the silk thread for *Samarang*'s Fox type several times. The captain claimed to have become highly adept at using this apparatus for intensity observations. As for using the weights in combination with the deflectors, Belcher assured Fox that he had 'paid attention to your wish relative to the Intensity by the Deflectors but until they give me a little more time for play I despair of performing any thing properly'.[44] What he required was more experience with the instrument, but finding time for this was tricky, given Belcher's duties as captain.

We were undeniably fortunate with the weather. While we frequently encountered conditions that undermined experiments, it was not until our return to the British Isles that we encountered the potential damage a rough sea could inflict on a magnetized needle. Our passage from the Bay of Biscay, past the Scilly Isles, to the Bristol Channel was marked by a strong rolling sea and gusty winds, which caused the needle to tap violently against its axle. This problem of vibration would have been constant to nineteenth-century expeditions: a dipping needle was never more than a storm away from

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[41] Clark Ross, *op. cit.* (note 39).

[42] Owen Stanley, Letter to Robert Were Fox, 6 April 1847, MS/710/110, Robert Were Fox Papers, RS.

[43] Stanley, quoted in Levere, *op. cit.* (note 18), p. 155.

[44] Edward Belcher, Letter to Robert Were Fox, 4 September 1845, MS/710/18, Robert Were Fox Papers, RS.

losing its magnetism. Geographically, it is significant that the majority of expeditions would have crossed Biscay, a notoriously rough region, on their way to the Southern Hemisphere. Growing inconsistency was a constant problem for magnetic observers. In 1845, Belcher reported that his needle C did not oscillate 'well and requires a heavy dose of the magnet to cause it to act properly'.[45] In April 1844, at Manila, Belcher's three needles had coincided extremely closely, but by Borneo the dips for needles A, B and C were varying by up to five minutes. He experienced further inconsistencies in the Korean Archipelago, where C read 12°30′ compared with A's 48°42′ and B's 48°45′37″. This was wildly inconsistent. Then at Nagasaki, A and B read 44°44′25″ and 45°6′2″ respectively, before differing by more than four minutes in the Japanese Rykukyu Islands. Belcher suspected that tropical heat was the cause of these erratic results.[46] Dayman too reported a gradual loss of magnetic strength with travel. Throughout his voyage aboard *Rattlesnake*, his three needles increasingly diverged, with each giving an identical dip of 62°44′9″ at Port Jackson, but with needle A's 59°37′6″ differing from B and C's respective measures of 59°44′2″ and 59°28′1″ at New Zealand. On reaching Port Stanley in 1850, Fox A read 52° 19′6″ compared with B's 51°43′3″ and C's 50°58′8″. Experiments made later at the Azores confirmed this growing inconsistency.[47]

Whereas vibration at sea tended to diminish our magnetic needle's strength, a far greater disturbance was encountered during overland travel. At sea, the needle's soft tapping on the circle's axle coincided with the ocean's swell, but this was a gentle motion for all but the roughest of conditions. On land, however, transporting the instrument by car caused a far harsher impact between the needle and the axle. This difference is hard to account for, but the needle's oscillations are undoubtedly better suited to oceanic travel. Nineteenth-century experimentalists may not have had to worry about travel by car, but overland expedition work frequently damaged Fox's dipping needles. In April 1843, Henry Lefroy commenced his surveying of the Hudson Bay Territory, employing canoes and wagons to transport his magnetic instruments. During these travels, Lefroy's Fox type was 'shaken to pieces', while needle C lost its magnetic force owing to the jolting of the carts.[48] Here, the Fox's inappropriateness for land surveying became apparent. From our experiences, it would seem that the crucial difference between overland and oceanic travel is that at sea, there are few sudden sharp shocks and the needle's oscillations are gradual; on land, there are far more sudden vibrations which jar the instrument, demagnetizing it and threatening to damage the pins and pivots on which the needle rotates.

On those occasions where our needle did lose its magnetism, or in equatorial waters where it was hard to know how effectively the needle was behaving, it became necessary to remagnetize the device. This was a difficult process. First, the pivots holding the needle in place have to be freed. Once the needle pops out, it has to be held firmly while being stroked in a constant direction with a powerful magnet, imparting a strong dose of magnetism. It then needs to be placed back in the circle, with the needle's pins aligned with the instrument's jewelled pallets. Aligned, a screw on the circle's rear is then tightened, slowly, to bring the pivots together and hold the needle in place: if too tight, or should the alignment be lost, the pallets will snap the needle's pivots, which are so

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[45] *Ibid.*

[46] *Ibid.*

[47] Dayman, *op. cit.* (note 39), p. 341.

[48] Goodman, *op. cit.* (note 1), pp. 123–124.

extraordinarily fine as to only just be visible to the eye. At the same time, without sufficient tightness, the needle will not oscillate, but fall from the pallets, risking the breakage of the pivots. The whole business of reinserting a remagnetized needle is the hardest task of maintaining a dipping needle, and therefore was only resorted to when absolutely necessary. I performed this twice, first at sea at the Equator, and second after the rough weather off the Scilly Isles. For nineteenth-century experimentalists on expedition, this process must have been incredibly anxiety-inducing, with the knowledge that the sudden snap of a pivot or damage to the jewels would render the entire instrument useless, since the level of craftsmanship required to repair a needle would be well beyond any member of the crew.

For all this, the dipping needle's overall performance was impressive. It gave consistent results and, with experience, we came to understand how it was operating and what steps could be taken to ensure that it was still measuring terrestrial magnetism. The application of deflectors allowed the detection of changes of magnetic force in regions where this force was minimal; the purpose of the deflectors for dip measures was, at first, unclear, given that the needle records dip accurately. But by applying this constant in places where it was not needed, such as around the British Isles, it became possible to examine relative changes in dip and intensity in regions where it was hard to observe magnetic phenomena, in lower latitudes. The greatest risk was that the instrument appeared so well fashioned as to take on an authority of its own. It was very easy to see the needle's smooth oscillations and fine craftsmanship, and trust it implicitly. The instrument, in this sense, took on a credibility of its own, seeming to give accurate measures from nature without the intervention of human manipulation. However, it was crucial to constantly check the needle's magnetism and to question measures, for which the deflectors were invaluable. Presumably, the weights would also have been of considerable worth to this constant testing, had conditions allowed. In effect, the Fox type was not so much a single instrument, as a rich package of apparatus that allowed its users to scrutinize both the Earth's magnetic properties and the integrity of the needle itself.

One limitation we encountered was in terms of written instructions. Fox published several guides on how to use his instrument throughout the 1830s, before he and Sabine collaborated on redrafting these for naval use during the 1840s.[49] Under considerable direction from Sabine, Charles Riddell published a revised set of instructions in 1844, before Sabine contributed his own, further refined, account to Herschel's 1849 *Manual*.[50] On reading these various accounts before becoming acquainted with the needle itself, I must confess to being somewhat perplexed at the precise advantage of using the deflectors and weights in combination or in which circumstances the deflector, or deflectors, alone should be employed. Likewise, the purpose of deflector experiments in regions where dip was perfectly observable was vague, and I did not perform these in my earliest trials. Given the constant rewriting of manuals throughout the 1830s and 1840s, along with reports from naval officers of growing confidence with their apparatus, and Fox's own insistence that future experimentalists attend periods of training with him at Rosehill and Penjerrick, it

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[49] Proof with Fox's annotations, 'Instructions for using Mr. Fox's Instrument for determining the Magnetic Inclination and Intensity', *ca* 1842–1843, 9942/34, CUL.

[50] C. J. B. Riddell, *Magnetic instructions for the use of portable instruments adapted for magnetical surveys and portable observatories, and for the use of a set of small instruments adapted for a fixed magnetic observatory; with forms for the registry of magnetical and meteorological observations* (Her Majesty's Stationary Office, London, 1844); E. Sabine, *op. cit.* (note 31).

would seem that the manuals struggled to deliver their intended instruction. As Felix Driver and Charles Withers have shown, this was a moment in which natural philosophers struggled with the challenge of using inscription to discipline the collection, sketching, cataloguing and describing of nature over great geographical space, and it was Herschel's *Manual* that marked a particularly successful work of this nature, proving popular with naval officers and remaining in print well into the 1870s.[51] Inscription provided a valuable medium for forming scientific habits among the Royal Navy's officer class. However, I would speculate that the number of revised texts on magnetic experimentation reflected the difficulties of describing the practical task of conducting such observations to expeditionary officers. In such cases, there was no substitute for direct experience.

In particular, our experiments demonstrated the importance of touch and sight in the operation of a Fox type. We found the instrument's vernier very precise, this being divided in such a way as to effectively read off measures in degrees and minutes. Each half a degree could be halved again by aligning the vernier's outer dial with an inner dial to give fifteen minute fractions, and it was easy to gauge measures to within five minutes of accuracy. The precision of our values was based on calculating the mean from a series of readings, with the observation of fractions of a minute, or seconds, completely impossible. The accuracy of this divided vernier was paramount, as James Fitzjames found on Franklin's 1845 expedition. Writing from *Erebus*, he claimed that he was 'terribly disappointed with my Fox which is *rotten*', and explained that the instrument was useless, having 'being cut only to degrees'. Without minute divisions, Fitzjames could only estimate 'to every 5'—and even if I could estimate to two minutes I would put no value on the results'.[52] The lack of an accurate vernier undermined all of his efforts.

Accurate measures from the vernier depended on coordination between visual observation and the feel of the ship's roll. There was, at moments of equilibrium, an optimum moment where the needle was balanced to show dip without the sway of the sea. Concurrently, along with aligning one's eye through the magnifying glass to read off the fractions of degrees, and keeping track of the feel of the ocean's swell, one hand had to be employed with the ivory disc, gently rubbing the pin at the rear of the device, to eradicate friction and ensure that the needle oscillated freely (figure 9). Thus there were two elements of touch to be coordinated with a visual reading. A second experimentalist to write down recorded dips was invaluable and it would be hard to perform a reading without assistance. The second sensual skill to attain, beyond the physically demanding task of carrying the weighty instrument in its protective box, was that of re-magnetizing the needle. To loosen and then reaffix a magnetized needle required holding the device, facing away from you, while undoing or tightening the rear screw that controlled the pallets. It is very hard to see the needle's pivots enter the jewelled pallets, so this process is not just a question of increasing or releasing pressure, but feeling for any moment at which one of the needle's pins might have popped out of its alignment with the pallets. Feeling this involved sensing any disturbance transmitted through the pallets to the screw itself, which was very slight owing to the delicacy of the pins. Listening was also important, with the ear invaluable in detecting any scratching of the pivots on the pallets that might give a warning of a

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[51] Charles W. J. Withers, 'Science, scientific instruments and questions of method in nineteenth-century British geography', *Trans. Inst. Br. Geogr.* **38**, 167–179 (2013), at pp. 173–174; Felix Driver, 'Distance and disturbance: travel, exploration and knowledge in the nineteenth century', *Trans. R. Hist. Soc.* (6th Series) **14** 73–92 (2004).

[52] James Fitzjames, Letter to Edward Sabine, 11 July 1845, BJ3/17, Sabine Papers, TNA.

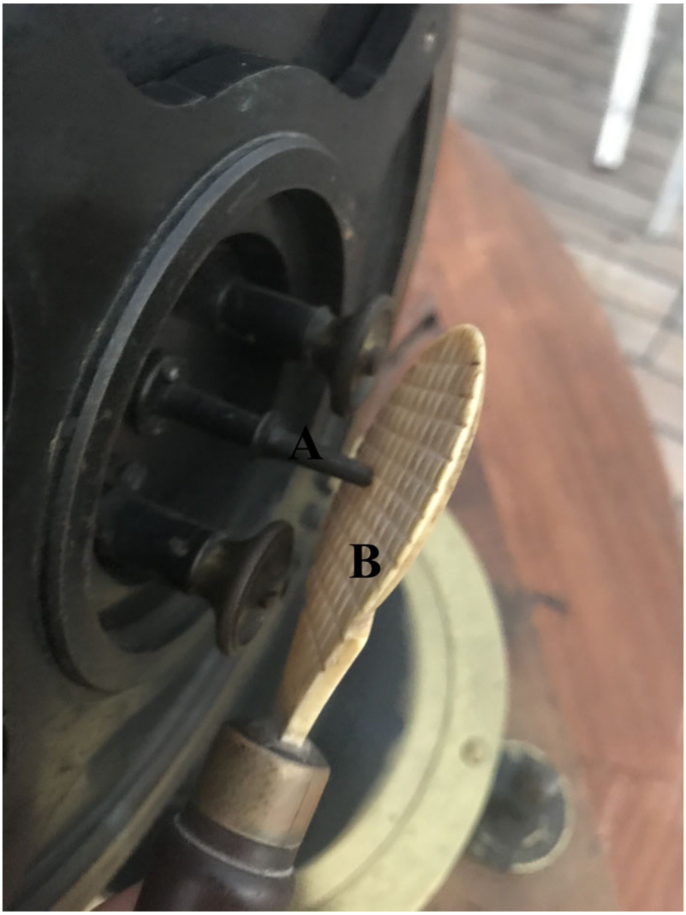

Figure 9. Vibrating the pin (A) at the rear of the circle with the ivory disc (B), which in turn vibrates the needle, encouraging an easy oscillation and accurate measure of dip. (Author's image, 2020.) (Online version in colour.)

forthcoming break: reinserting the needle was a silent process, with the experimentalist ever listening for the dreaded crack of snapping pivots. I am pleased to say that this sound was one we never encountered. But in this task, sight was of a very limited value compared with touch and hearing.

Conclusion

The BMS's effectiveness and ability to produce credible magnetic data were not just reliant on controlled experimental sites, reliable instruments, and well-instructed officers. Crucially, they also depended on the judgement of these experimentalists to know when their instruments were behaving efficiently and to distinguish between instrumental errors, local magnetic disturbances, and the Earth's magnetic influence. Understanding how magnetic characteristics could change over time and space required the accumulation of extensive measurements but, for the BMS's earliest observations, it was difficult for experimentalists to know precisely what to expect as they voyaged over great distances. In these instances, accumulated experience was invaluable. Only by performing a sufficient number of magnetic experiments, and through a close acquaintance with their instruments, could naval officers develop an understanding of how accurate a set of experimental measurements might be. There was, therefore, a considerable element of premeditation to a successful magnetic experiment. In equipping later expeditions with an increased number and range of magnetic devices, the BMS, under Sabine's leadership, attempted to remove this dependence on human judgement from the production of magnetic knowledge. And yet, without question, experience and built-up experimental skill remained irreplaceable. A Fox type included a rich body of appliances, including deflectors, spare needles, and weights, that not only tested for terrestrial magnetic properties, but also trialled the instrument itself. The question of when to apply, of how to arrange, and of which combination of apparatus was appropriate to use at a given time or place was down to the knowledge of the experimentalist on the spot: these decisions had to be made far from the direct instruction of Fox at Falmouth and Sabine at London. Whereas this would fall within Sibum's categorization of gestural knowledge, or tacit knowledge, both terms fail to adequately define the sort of understanding required to manage a Fox type through an expedition. This was not just a matter of practical abilities gained through experience, but it involved a considerable intuitive element, relying on emotional, subjective feeling rather than specific learning. Magnetic experiments involved a combination of tacit and intuitive knowledge, uniting experientially attained skill with a sense of how a magnetized needle was behaving, which was often shaped by anxiety over the instrument's condition and uncertainty over the local influence of terrestrial magnetism.

Published accounts such as Sabine's 'Contributions' emphasized the BMS's standardizing procedures and instruments, and systematizing credentials; but, in practice, this scientific enterprise was a complex balance between disciplined experimental techniques and experientially grounded intuition. It was on the effectiveness of this relationship that the credibility of this global scientific experimental inquiry relied. Fox's dipping needles could be robust instruments of survey science: their reputation was not unjustified. However, the trustworthiness of the data produced by these devices was inseparable from their user's ability to constantly check their performance and assess their temperamental nature. The production of an empirical understanding of terrestrial magnetism relied on a systematization of experimental practices that, ideally, eradicated human judgement. Despite all this, on-the-spot intuition and the experimental skill of naval officers remained essential to the operation of this regime and the cultivation of knowledge of the Earth's magnetic phenomena.

Data accessibility

This article has no additional data. All the data contained herein are the author's own.

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