Earth's Magnetism in the Age of Sail

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For many centuries, the source, behavior, and even the essential nature of geomagnetism were enigmatic. Despite this, the effect of geomagnetism was familiar, by imparting a directional preference on the magnetized needle of the compass and providing a useful, if somewhat annoyingly complicated, reference for navigators. Although the compass seems to have first been invented in China, it was the Europeans who made the most systematic early studies of magnetism, who made the first elaborate and practical usage of the compass, and who developed most of the early theories as to the cause of the compass needle's north-seeking tendency. From the centuries of the Middle Ages, through the late 16th century of the Renaissance, to the 17th century of philosophical enlightenment and the 18th century of discovery, the subject of magnetism and, more specifically, geomagnetism, evolved from a hodgepodge of mystical beliefs into something that we can today recognize as the object of modern scientific pursuit. Those same centuries witnessed the great transoceanic sailing voyages undertaken by European nations for reasons of exploration, territorial claim, religious mission, and mercantile trade. Naturally, the navigator's compass, and therefore geomagnetism, played an important role in these developments. This romantic intersection of science and history is the subject of *Earth's Magnetism in the Age of Sail*, a pleasantly written and scholarly book by A.R.T. Jonkers.

Earth's Magnetism is a review of the historical development of the science of geomagnetism and a summary of Jonkers's own quantitative analysis of compass-based navigation prior to the year 1800. It is a distillation of the author's massive doctoral dissertation, submitted as partial fulfillment of the requirements for a degree in nautical history from the Vrije Univeriteit in Amsterdam (Jonkers, 2000). I will be the first to admit that my review here is unconventional; it is longer than is usual because it summarizes and addresses some surrounding issues of relevance. A shorter, more classical-type of review can be found in Merrill (2003). Since I am not an historian, I cannot comment with authority on the proper placement of this study upon the broad ocean of navigational history, but, as a scientist, I am very much aware of its position upon the landscape of geophysics. Over the past several years, Jonkers, now at the University of Liverpool, has worked in close collaboration with Andrew Jackson of the School of Earth Sciences at the University of Leeds. Together with their colleagues, they have compiled geomagnetic data, mostly declinations from various locations and times, contained in logbooks kept in historical archives in Britain, France, The Netherlands, Denmark, and Spain (Jonkers et al., 2003; Jackson et al., 2003). And, in the process, they have dramatically increased the number of data available for geophysical and historical-navigational research. Models have been fitted to these data for purposes of research into the nature of the Earth's core (Jackson et al., 2000) and research into the accuracy of historical navigational methodologies (Jonkers, 2003, concluding chapter). In the geophysical context, this important work is a continuation of historical data compilations and core-field modelling programs undertaken previously by others (e.g., Barraclough, 1982; Bloxham et al., 1989), which have benefited from the noteworthy initiative of David Gubbins, now also at the University of Leeds. Although geophysics has certainly been a beneficiary of the work of Jonkers and his colleagues, it must be said that *Earth's Magnetism* is mostly a record of the historical analysis part of a much larger inter-disciplinary project.

1. Oceanic navigation

Much of the original motivation for scientific study of geomagnetism stemmed from a practical desire to use the compass for navigational orientation and position finding. During the age of sail, traversing the vast and relatively featureless ocean was much more challenging and dangerous than just routinely plying coastal routes. To ensure arrival at a remote port of destination, regular estimates of position and heading were needed, and so, because of the risks and uncertainties involved, navigators employed a number of semi-redundant means for making those estimates (e.g., Hewson, 1983). On a clear day (night) latitude could be determined by measuring the height of the Sun (stars) above the horizon or by measuring the angular difference between directions defined by solar (stellar) rising and setting. With respect to heading, on a clear day (night), the highest, noon point of the Sun (Polaris at any time) could be used to estimate north.

However, reasonably accurate estimates of longitude were much less easily obtained. In principle, longitude could be determined by a chronometer, set, for example, to the local time at home port. Then, using the Sun (stars) to give a local time at sea, the time difference could be used to estimate longitude. But keeping sufficiently accurate time with an on-board clock was difficult, because the motion of the ship tended to perturb the horological motion, and because temperature changes, humidity, and the corrosive affects of sea salt all could, over time, interfere with or degrade the clock mechanism. Alternatively, one could observe lunar occultations or other predictable astronomical events to obtain a universal time, which could, instead of a mechanical clock, be used to determine longitude. But making the precise astronomical observations on a ship deck that was rocking back and forth was tricky, and interpreting ephemerides and making the requisite calculations took skill that not every ship master possessed.

Until the 1760s, when John Harrison constructed a sea-worthy chronometer of reasonable reliability, longitude was usually estimated, rather crudely, by dead-reckoning the combined effects of ship speed and drift caused by wind and current. An estimate of longitude for a given day was usually based on the estimated change in longitude since the previous day. Therefore, longitude estimates tended to accumulate growing errors, and these would not usually be corrected until a land sighting allowed for positional certainty. Sensibly, routes were often set along a fixed latitude, sailing east or west until the desired port was reached. But for long voyages to many destinations, particularly island destinations, which might easily be passed by, or when specific hazards had to be avoided, more exact estimates of longitude were desired.

Of course, cloud cover or fog could make impossible all astronomical observations used for estimating latitude, longitude, and orientation. In such cases, the compass served as an important backup, especially if declination, the horizontal angle between the direction of compass needle and true north, was known or estimable. With respect to its direct measurement, with an astronomical fix on north and a compass, magnetic declination could be easily measured. Declinational data were routinely recorded in the ships' logs, along with time, estimated location, and other bits of information judged to be of significance. Oftentimes, local declinational measurements served to reinforce the navigator's own estimate of heading and location. Occasionally, more elaborate attempts were made to use magnetic declination to invert for longitude, sometimes in combination with latitude and magnetic inclination, that is, the dip of a freely orienting magnetic needle in the vertical plane. But these efforts were unsuccessful, in part because the global magnetic-field function is so complicated, and knowledge of it was so inadequate, that performing an inversion for longitude was simply impractical.

As an example, Jonkers (2003, p. 31) recounts the story of James Moore, who, in 1790, concocted an ill-conceived method for estimating longitude using magnetic declination, based upon an instrument he designed but the details of which he never revealed. With naïve confidence he sought to demonstrate its utility when sailing from England to the West Indies. Moore and his crew set out aboard the *Maria of Cork*, but after leaving port they were neither seen nor heard again. With the likelihood that the crew lost their way, a disastrous end to the voyage has been inferred.

2. Progressive conceptualization

In order to exploit the directional properties of the compass, it was necessary to have accurate charts of magnetic direction and to appreciate their utility and their limitations. This, in turn, required a scientific understanding of both magnetism and geomagnetism. I imagine that it is the development of this understanding that is of most interest to the geophysicist reader. Therefore, drawing heavily upon Jonkers's book, but also making usage of other source material, I've chosen to highlight here a particular thematic thread that runs through the first half of *Earth's Magnetism*: the secular acceleration, up to the year 1800, in the conceptualization of the geomagnetic field in terms of its time-dependent, physical form at the Earth's surface, where the influence on a freely-orienting magnetized needle has been measured and mapped, and in terms of its physical nature, as described by the more abstract laws of physics.

While occasionally punctuated by significant leaps forward, this conceptual progression has been mostly incremental. More specifically, over time models and maps of the surficial geomagnetic field have improved, becoming, as they are now, consistent with a larger potential theory of magnetism. They have also gradually become more complicated, but (usually) only insofar as such additional complexity has been required by observation and data. Of course, this evolution has never ended; it continues to this day, as exemplified by the modelling effort (Jackson et al., 2000) conducted in conjunction with the historical analysis discussed in *Earth's Magnetism*.

3. The dipole

Jonkers's review begins in the Middle Ages, when geomagnetism first began to emerge as a well-defined scientific discipline, arising simultaneously with a more general philosophy of science and its gradual divergence from mysticism. The few written records of magnetism from this era are probably best regarded less as specific documentations of originality and more as representations of the prevailing thought of their time. For the modern-day reader, one of the striking qualities of these ancient documents concerned with magnetism is the apparently loose and unusual usage of vocabulary. Medieval natural philosophers were, of course, struggling to define and explain some pretty rudimentary scientific concepts, yet they did not have the elaborate and refined terminology that we have today, and which we often now define against a mathematical framework.

An early and prominent example of magnetic analysis from the Middle Ages is that of the nobleman, Petrus Peregrinus (1269). He recorded his observations of the attractive and repulsive properties of lodestones (Smith, 1968; Jonkers, 2003, p. 42). He defined, qualitatively and probably not completely originally, the notion of a dipole. Peregrinus also made the first known European descriptions of a compass consisting of a freely-pivoting magnetic needle, something he clearly expected would be useful for navigation. With respect to explanation of the phenomena of magnetism, well, this is where things get interesting. Peregrinus believed that magnetism was a universal quality that existed by virtue of a sort-of "sympathy" between similar celestial forms. He held that spherical lodestones had a real and tangible correspondence with the whole cosmos, and not just the Earth.

Accordingly, Peregrinus thought that lodestones by virtue of sympathy, would seek alignment with the axis of the entire celestial sphere, about which it was observed that the stars rotated with clockwork regularity. Furthermore, he expected that a compass made from a lodestone should show zero declination everywhere, since he presumed that alignment with the cosmic axis would be perfect, and that once this alignment was attained, lodestones should exhibit spontaneous diurnal rotation, they being motivated to perpetual motion through an active unification of stone and sky. That lodestones do not, in reality, possess such properties is not so much a reflection of Peregrinus as it is a reflection of the whole Medieval era. There had not yet developed a tradition of rigorously checking theoretical speculation against reproducible experimental results. In any case, it is amusing that subsequent investigators (Jonkers, 2003, p. 73) hypothesizing a sympathy between stone and Earth, would cite the lack of spontaneous rotation by lodestones as evidence that the Earth doesn't actually rotate!

4. Declination and inclination

By the 16th century, with numerous measurements of declination having been collected during overseas voyages, the simplistic suppositions of Peregrinus were effectively invalidated. Instead of declination being zero as Peregrinus expected, declination was proving to be non-zero almost everywhere[1]. More specifically, typical, root-mean-square values of declination along the equator are $\sim 7^\circ$, with larger values occurring, of course, near the geomagnetic poles. In the search for an explanation, attention was diverted from the heavens as theories of magnetism and the compass gradually became more terrestrial-based. In-

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[1] Thankfully, Jonkers does not delve much into the murky issue of who discovered declination. This is addressed in detail by Mitchell (1937).

spired by Ptolemaic myth and Arabian folklore, some philosophers sought to account for the deviation of the compass from true north by supposing the existence of a large lodestone mass, or magnetic mountain, emplaced at some high-latitude geographical location (Jonkers, 2003, p. 44–46). Some even claimed to have found it. . . one place: at the intersection of four seas and between four islands, somewhere in the Arctic. The search for the magnetic mountain became more systematic when the Flemish cartographer, Gerhard Mercator (1546), estimated its location by extrapolating declinational data from various locations to a particular geographical point.

Then the London compass maker, Robert Norman (1581), published his recordings of magnetic inclination, observations that led him to conclude that the point of "respect" for the compass was not on the Earth's surface, but was, instead, within the Earth itself (Good, 1991; Jonkers, 2003, p. 62). This discovery influenced William Gilbert (1600), whose publication of his investigations into the magnetic properties of spherical lodestones represents an important milestone in the history of experimental science (Hesse, 1961; Malin and Barraclough, 2000; Jonkers, 2003, pp. 66–71). This English physician's analyses were more objective and scientific than those of Peregrinus, but Gilbert's thoughts, like those of others living during the era, were intimately infused with animism. When Gilbert dubbed his lodestones to be "terrella", or small Earths, he was doing so out of a belief that they were the almost literal living children of mother Earth. Therefore, by investigating terrella one was, in effect, investigating the properties of the Earth as well. And, since the terrella and the Earth exhibited certain common magnetic properties, such as inclination as a function of latitude, then it seemed reasonable for Gilbert to conclude that the Earth was a giant lodestone. But Gilbert was aware of the geographic complexity of the compass needle's directionality, something he attributed to a distortion, caused by the continental land masses, of an otherwise simple global magnetic directionality.

5. Tilted dipoles

Renaissance Iberian cartographers were the first to consider the depiction of magnetic directionality by a tilted "dipole" (Jonkers, 2003, pp. 49–51). In 1514, the Portuguese navigators, João de Lisboa and Pedro Anes, gave the longitude of the (north geomagnetic) pole for such a tilted dipole model: its agonic line (zero declination line) fell through the Azores, but, rather oddly, they left the latitude of the pole unspecified. It was not until almost a century later, in 1602, that the Spaniard, Pedro de Syria, introduced a tilted dipole with a specified polar latitude. These efforts, and those of others of other nationalities who proposed variations on the simple dipole model, were usually intended to resolve a handy mathematical rule for determining longitude as a function of declination. But with the growing number of published sailing records containing compass measurements, toward the end of the 16th century it was becoming clear that declination could not be represented by a simple dipole.

6. Multiple poles

In 1596, the Spanish mathematician, Francisco da Costa, produced a map with four agonic lines—the first multipolar geomagnetic model (Jonkers, 2003, pp. 53–61). Soon thereafter, in 1598, the Flemish preacher, Petrus Plancius, devised his own quadrupolar model, and in 1599, the Dutch scholar, Simon Stevin, introduced a sextupolar model. And so, descriptions of geomagnetism were tending towards increasing complexity, but they were also often highly arbitrary, with the numbers and positions of poles and agonic lines being fixed for reasons having as much to do with aesthetics and prejudice as with actual cartographic accuracy. In fact, none of these models gave a particularly accurate representation of the global declination function. Nonetheless, since overseas navigation was now becoming extremely important, the need for more survey data, to ensure that model features and maps could be more accurately constructed, was becoming apparent to those involved.

7. Secular variation

New dimensions to the subject of geomagnetism were ushered in during the 17th century. After comparison of a number of measurements taken in London over several decades, the English mathematician, Henry Gellibrand (1635), announced that magnetic declination changes with time. Specifically, Gellibrand found that the declination at London was decreasing by $\sim 0.13^\circ$ per year. This observation was soon confirmed by others, and, in 1676, Henry Bond, an English mathematician and navigational teacher, proposed a dynamic magnetic longitude scheme based on a precessing dipole, with the magnetic poles slowly and steadily migrating in a westward direction about the geographic poles (Howarth, 2002; Jonkers, 2003, pp. 85–89). This model became deeply embedded in the navigational literature, even though gross discrepancies with data were almost immediately noted. More generally, what was developing was a routine expectation of consistency between the models and the, now quite obvious, secular variation.

8. Time-dependent, multiple poles

Afterwards, time-dependent, multipolar models were proposed. Most prominent among these were those proposed in by Edmond Halley (Halley, 1683, 1692), the English astronomer whose name is most commonly associated with the comet that bears his name, but who also made substantial contributions to geophysics (e.g., Bullard, 1956). Extrapolating from his own observations on the effects of two or more lodestones, Halley modelled geomagnetic directionality in terms of four poles, two in the crust and two anchored to an interior "ball", neither of which had antipodal symmetry. Halley supposed that the interior ball was separated from the overlying crust, and that it could rotate with respect to the surface, thereby producing the observed secular variation of declination (Kollerstrom, 1992; Jonkers, 2003, pp. 90–95). Although different in detail from what we know today about the Earth's stratified interior, Halley's hypothesis was certainly remarkable for its time.

These conceptual developments did not, however, occur in a vacuum. Halley was well aware of observations indicating that the global declination function was both geographically complicated and time-dependent. Furthermore, there is some evidence, the entire significance of which is difficult for historians to ascertain, that Halley was strongly influenced by Peter Perkins, an English mathematician who proposed, through unpublished, verbal presentations given before the Royal Society of London, that declination could be modelled by four moving poles (Jonkers, 2003, pp. 90–95). More generally, Halley was also influenced by rapid developments in the theories of forces, which were beginning to be conceived within a larger and unifying mechanical and quantitative framework (e.g., Thrower, 1990).

9. Mechanistic theories

Jonkers makes very careful and sparing usage of the word "field". This is for good reason: for pretty much the entire historical window of time covered by *Earth's Magnetism*, attraction and repulsion at a distance between magnetic objects was observed and geomagnetism had begun to be mapped on a global scale, but these subjects were not explained with terms and concepts that we would today recognize as belonging to a general field theory. Peregrinus and Gilbert made what were essentially qualitative, descriptive accounts of magnetism, drawing analogies with living beings and seeing teleologistic intent. In a clear break with ancient dogmatic thought, Descartes (1644) advocated a scientific philosophy that was more practical than that of his predecessors. In his rigid rationalism, appealing to spiritual notions and divine purpose was unnecessary. Instead, scientific theories could be considered successful if they could make mechanistic predictions of observations (Hesse, 1961; Jonkers, 2003, pp. 80–81).

To account for magnetic action at a distance, Descartes suggested that an aether, composed of interlocking vortices or "tourbillons", supported the continuous flow of infinitesimal particles along magnetic lines of force, with a channeling of the particles along the inside of magnetic objects. According to his theory, a compass needle would turn so that its magnetic channels would be parallel to the path taken by the flow of Earth's magnetic particles. Descartes's theory is often described as corpuscular, but with some accommodation for differences in vocabulary it also clearly possesses some of the properties of a field theory. Of course, a more precise elaboration required mathematics that were undeveloped at the time of Descartes. The necessary quantitative foundation would be established when the great English physicist and mathematician, Newton (1687), introduced his laws of universal gravitation. Curiously, Newton did not direct his attention to magnetism, but his success in quantifying gravity provided a powerful example of how to proceed. Moreover, Newton (1711) and Leibniz (1684, 1686)would go on to invent calculus, a revolutionary development in its own right and the basic mathematical formalism needed to fully describe a continuous media, such as the geomagnetic field.

Jonkers does not go into additional detail on the development of mathematics. This I can understand, since prior to 1800 mathematics was not very securely integrated into the subject of geomagnetism. Nonetheless, it is worth noting that mathematics was progressing parallel to geomagnetism, and, indeed, much of the mathematics we use today for modelling the main part of the geomagnetic field was developed in the 18th century. For example, the Swiss mathematician, Euler (1736), through his study of inviscid fluids, and the French-Italian mathematician, Lagrange (1773), through his study of gravitation, established the foundations of potential-field theory. The French mathematicians, Legendre (1784) and Laplace (1799-1825), discovered, respectively, the axisymmetrical and non-axisymmetrical, spherical-harmonic decompositions of potential fields. With respect to analyzing geomagnetic data, the method of least-squares, used today for fitting spherical harmonics to magnetic-field data (among myriad other very obvious applications), was invented by the great German mathematician and physicist, Carl F. Gauss, in the closing years of the 18th century when he was, incredibly, just a teenager (e.g., Plackett, 1972).

10. Data collection, compilation, and usage

If the first half of *Earth's Magnetism* is about the gradual condensation of concepts and theories about the geomagnetic field, the second half is concerned with the practical issues of navigation, and how, specifically, to exploit the compass given that its directional properties are such a complicated function of space and time. The geophysicist reader will certainly be interested in the discussion of specific voyages of exploration and discovery, which often included magnetic surveys, and in the evolution in thought about how to display geomagnetic data on a map. Jonkers discusses estimation and measurement methodologies, and data collection during routine oceanic voyages, which were recorded by mariners who happened to be on their way from one place to another. Many of the voyages were associated with mercantile organizations of historical notoriety, such as the Hudson's Bay Company, the English East India Company, the French Compagnie des Indes, the Dutch Vereenigde Oostindische Compagnie, and others. Because of the growing importance of global trade and colonization after the mid-17th century, the numbers of available data increases dramatically (see also, e.g., Jackson et al., 1997). In all, Jonkers, with the assistance of colleagues, reports on the inspection of 2062logbooks producing 51,306 declinational measurements taken during the years 1590–1800, a quantity of data which, by itself, is a significant contribution to the disciplines of geomagnetism and nautical history. In the final chapter of *Earth's Magnetism* Jonkers uses these newly available data, together with a field model, to make quantitative comparison of the navigational methodologies of various nations, a subject that might interest an historian, but which, I suspect, will not interest the typical geophysicist reader.

11. Contour maps

Today, we often make visual representation of spatial functions by plotting contour lines of constant value. Interestingly, the notion of contours first arose in the 1530s in the context of a tilted-dipole model of declination, that proposed by the Portuguese cartographer, Alonso de Santa Cruz (Jonkers, 2003, p. 186). But the“isogonic” contours of constant declination on his map (now lost) were simply predictive, they were not actually representations of data. In 1584, the Dutch surveyor, Pieter Bruinsz, made the first known contour display of the nontrivial complexity of real data, isobaths showing water depth (e.g., Robinson, 1982). The particular distinction of making an isogonic representation of actual magnetic declinational data is assigned to the Italian Jesuit and navigation teacher, Christovao Bruno. His map, made in the 1620s (now also lost) encompassed both the Atlantic and Indian Oceans and was based on the published navigational records of sailors and Bruno's own measurements made during sea journeys to India (Jonkers, 2003, p. 187). The significance of these developments can hardly be overstated. They represent a focusing on the characterization of the actual physical form of nature and, in particular, the directional properties of the Earth's magnetic field, rather than simply the repeated generation of simplistic models having little basis in reality. This was appreciated by Halley (Thrower, 1996, p. 275; Jonkers, 2003, p. 187), who would himself go on to make important contributions to magnetic data collection and declinational cartography.

12. Scientific voyages and global charts

The first oceanic voyages dedicated specifically to scientific research were those of Halley. Setting sail in 1698, in command of the Royal Naval vessel the *Paramore,* Halley made frequent measurements of latitude, magnetic declination, and (when possible) he calculated longitude by observing eclipses of the moons of Jupiter to estimate universal time. Upon his return, in 1701, Halley published a chart of declination for the Atlantic, based on his own data, and in 1702 he published a chart of declination for the Atlantic and Indian Oceans based, in part, on data collected by others. Today, these charts are considered to be of historical significance, since they are the oldest isogonic charts still in existence and because, at the time, they generated much discussion among scientists, cartographers, and navigators (e.g., Barraclough and Clark, 2001). Halley hoped that his charts would help in the determination of longitude, at least insofar as the charts remained accurate. However, because of secular variation it was clear that regular updates would be needed. Indeed, in 1710, the French cartographer, Guillaume Delisle, noted that the rate of change of declination was not predictable and that it could not, for example, be represented by a simple westward drift (Jonkers, 2003, pp. 188–189).

Unfortunately, from the standpoint of modelling the geomagnetic field using historical data, early seafaring surveyors, including Halley, made less frequent measurement of inclination. This was probably due to the fact that inclination was not considered to be as useful as declination, and, in any case, its measurement was more difficult to make on board a rocking deck than was that of declination; the vertical plane of a dip needle must be aligned with the magnetic meridian and measurements need to be made relative to a stable horizontal plane. Given Jonkers's own emphasis on navigational history in *Earth's Magnetism,* it is perhaps not surprising that he does not discuss the development of inclinational, or "isoclinic", charts, although I note that there is a short discussion of the matter in his thesis (Jonkers, 2000, pp. 381–382). The subject is, however, certainly of interest to geophysicists. Credit goes to the Cambridge professor, William Whiston, for producing the first known isoclinic charts (e.g., Howarth, 2003). But his maps, published in 1721, were confined to Southern England, were heavily biased by Whiston's simplistic notion of a precessing-dipole model of geomagnetic directionality, and they are, in fact, very much inconsistent with the hindcasting field model of Jackson et al. (2000). The first global-scale isoclinic chart making a realistic depiction of inclinational data was that produced by the Swedish physicist, Johann C. Wilcke (1768). His map, based on magnetic-dip measurements made by individuals of several nationalities, has not, in my opinion, received the attention that it deserves.

Finally, because it was not being measured until very late in the 18th century and because it too was not generally considered to be of use to navigators, early measurements and mappings of geomagnetic intensity are not addressed at all in *Earth's Magnetism*. Briefly, the oldest surviving records indicating geographic differences in field intensity are those due the French captain, Elisabeth P.E. De Rossel, who measured relative intensity by observing the oscillation rate of a magnetized needle during the 1791–1794 expedition of the *Bruny D'Entrecasteaux* (e.g., Lilley and Day, 1993). De Rossel noted, in particular, that magnetic intensity was greatest near the magnetic poles and least near the magnetic equator. This observation was rediscovered by the German naturalist, Alexander von Humboldt, who produced the first map showing relative intensity, published by von Humboldt and Biot (1804), with contours consisting of "isodynamics" over the northern part of South America. The first global-scale map of relative intensity was published by the Norwegian scientist, Hansteen (1826); also see, e.g., Brekke and Egeland (1986), but this came well after Jonkers's choice of an 1800 cut-off for his historical investigation.

13. Modelling the geomagnetic vector field

Of course, more can be said about the essential role of data collection and mathematical analysis in the historical development of geomagnetism. With the onset of the 19th century, the growing use of iron in ship construction contaminated compass data, and the new century saw the demise of the maritime mercantile companies, whose logbooks provided Jonkers and company with a valuable resource. Despite these changes, geomagnetic data useful for field modelling became very numerous in the 19th century, when they were being routinely collected at ground-based magnetic observatories[2] and during dedicated magnetic surveys on both land and sea. The invention of the absolute intensity magnetometer (Gauss, 1832) made it possible to measure and map the full-vectorial nature of the geomagnetic field. Theories of geomagnetism were unified with potential-field theory and with the quantitative, least-squares analysis of data by Gauss (1839), who used spherical-harmonic analysis to separate the geomagnetic field into internal and external parts, thereby showing that the majority of the field originated from within the Earth.

Since then, many researchers have applied a similar methodology, using data collected at or above the Earth's surface and fitting a truncated spherical-harmonic expansion to obtain a global field model corresponding to a particular instance in time (for a review, see Barraclough, 1978). This is, for example, the procedure adopted for constructing candidate models for the International Geomagnetic Reference Field (IGRF) every five years (e.g., Barton, 1997). It is superior, however, when constructing a model describing the field over a duration of time, to allow it to be a (non-constantly) variable function of time. So, for example, Bloxham and Jackson (1992) use a set of model basis functions consisting of spherical-harmonic splines. Data collected at different geographic locations and at different moments in time can then be fitted simultaneously and consistently. And, in this way, the informational content of the spatial and temporal correlations between the various data are exploited, something that is especially important for modelling historical epochs represented by relatively few data.

What is perhaps insufficiently appreciated within the field-modelling community is that fitting a prematurely truncated set of otherwise complete basis functions, such as spherical harmonics, to a set of data can yield a model that is overly sensitive to the (spatial and temporal) distribution of the data, that is unstable to errors in the data, and that is dependent on both the particular choice of basis functions and the level of truncation (e.g., Lowes, 1990); furthermore, excessive subsidiary structure and odd symmetries, akin to the Gibbs phenomenon seen in standard Fourier-type analyses, can result (Whaler and Gubbins, 1981). These difficulties stem from the fact that a complete basis-function expansion is too general. There exist an infinite number of different models that fit the data equally well, most having far more short-wavelength and high-frequency content than is usually desired. One resolution is to choose a model that minimizes a weighted combination of data misfit, as measured by χ^2, and model complexity, as measured by a model norm (Franklin, 1970; Backus and Gilbert, 1970). Such an approach, known variously as stochastic inversion, Bayesian inversion, damped least-squares, or regularization, is now being employed in studies of the Earth's internal magnetic field (Shure et al., 1982; Gubbins and Bloxham, 1985; Sabaka et al., 2002). It is also the methodology used to construct the global magnetic field model (*gufm1*) of Jackson et al. (2000) that covers continuously the years 1590-1990 and which is associated with the historical analysis presented by Jonkers in *Earth's Magnetism*[3]. Among the range of possible solutions, the preferred solution is the one of minimum norm that is consistent with the coherent signal in the data, a result that can be said to follow from the parsimonious principles of William of Occam, the medieval English philosopher whose proverbial razor cut away unnecessary hypotheses and whose appealing philosophy is often invoked by geophysicists (e.g., Constable et al., 1987).

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[2] And magnetic data are still collected at such observatories; see www.intermagnet.org for more information.

[3] Movies depicting geomagnetic secular variation can be found at http://geomag.usgs.gov.

14. Conclusions

For the geophysicist engaged in research, it is the model associated with this work, namely *gufm1* of Jackson et al. (2000), that will be of the most direct interest. This model and its ancestors have been used for estimating fluid motion at the top of the core, for constraining the angular momentum budget of the Earth, for studying core-mantle coupling mechanisms, and for comparison with paleomagnetic data and dynamo simulations. The outcomes of such applications are often very sensitive functions of the details of the field models being used. The hefty content of Jonkers's book assures us that much care and expertise has been devoted to the inter-disciplinary effort of compilation, treatment, and analysis of the original geomagnetic data used in constructing the field models. Although this book is probably not one that needs to be kept, right there, on every geophysicist's personal bookshelf, for those curious about the history of geomagnetism and, more generally, the history of science and its philosophical development, it is an extremely valuable resource. *Earth's Magnetism in the Age of Sail* is an adventurous voyage through a rich and eclectic sea of anecdotes, ideas, and people. Jonkers is to be congratulated for this success.

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