Routes, rutters, navigational techniques and the development of navigational aids in traditional Chinese seagoing: The case of the compass

*Routes, routiers, techniques de navigation et développement des aides à la
navigation dans les bateaux chinois traditionnels : le cas de la boussole*

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Routes, rutters, navigational techniques and the development of navigational aids in traditional Chinese seagoing: The case of the compass

Stephen Davies

Abstract

This paper will consider magnetic compasses as navigational aids in traditional Chinese seagoing in the light of the history and development of the science and technology of the magnetic compass. It will contend that in principle the magnetic pointers carried aboard traditional Chinese vessels (and equivalently equipped vessels elsewhere) before the late 17th century cannot have been reliable navigational aids and that no prudent mariner would have used them as such. The most widely accepted pre-17th century traditional seagoing compass water-bowl design will be evaluated according to the known, iron fastened, multi-cellular box girder structure of contemporary Chinese seagoing ships and to the waters in which they operated. A similar evaluation will be made of the post-17th century, dry pivot design. Both will be compared to the development of the magnetic compass, and of theories of geomagnetism and compass design between the 12th and 19th centuries in the west. Some conjectures will be ventured after the foregoing analysis as to the meaning and practical application of the “needle paths” associated traditional Chinese route maps and rutters.

Keywords

magnetic pointer, Needham question, needle paths (zhenlu), ship's motions, design principles, Laud Rutter, Selden Map, Yale Maps

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Résumé

Cet article considérera les aiguilles magnétiques comme des aides à la navigation dans la navigation traditionnelle chinoise à la lumière de l'histoire de la boussole magnétique et de son développement scientifique et technique. Il prétend qu'en principe les aiguilles magnétiques transportées à bord des navires chinois traditionnels (et des navires équivalents ailleurs) avant la fin du ^{xvii}^e siècle ne peuvent pas être des aides à la navigation fiables et qu'aucun marin avisé ne les aurait utilisées comme telles. La conception de l'aiguille magnétique flottante portée sur les bateaux chinois traditionnels avant le ^{xvii}^e siècle, la plus largement acceptée, sera évaluée à travers l'étude de la structure en poutres-caissons multicellulaires, attachée au fer, des navires de mer contemporains chinois, en prenant en compte les eaux dans lesquelles ils opèrent. Une évaluation similaire sera faite de la conception du pivot sec après le ^{xvii}^e siècle. Les deux seront comparées au développement de la boussole magnétique, et des théories du géomagnétisme et de la conception de la boussole entre les ^{xiii}^e et ^{xix}^e siècles à l'Ouest. Quelques conjectures seront faites suite à cette analyse quant à la signification et à l'application pratique des « chemins d'aiguille » associés aux cartes de route et aux routiers traditionnels chinois.

Mots-clés

aiguille magnétique, question Needham, trajectoires des aiguilles (zhenlu), mouvements du navire, principes de conception, Routier Laud, Carte de Selden, Cartes de Yale

Introduction

This paper had its genesis in my attempts to understand how what is known as the Selden or East/West oceans map was constructed and is to be understood, though only from the point of view of it as a vector of navigational information.¹ In engaging in this exercise, I found myself confronting data that, as a long time practicing navigator familiar with the three principal metrics of the navigator's calling – time, direction and distance – I found some difficulty in fully comprehending. I had stumbled across the same problem a few years beforehand trying to understand the fascinating sequence of what we can loosely call coastal views, that constitute what may have been a junk navigator's working rutter, now located in the Sterling Memorial Library at Yale University and sometimes known as the Yale Maps.² The problem had three elements, only one of which I shall focus on here. The elements I shall leave aside are the closely related – indeed in Chinese navigational terms possibly identical – measures of charted distances and time. That is not because these are less important – they are very important – but because there is neither time nor space to embrace them in this paper.

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Instead I shall turn to the fascinating and important issue of direction, for it is a widely accepted claim that this was a problem that Chinese navigators were the first to solve by the method with which we are all so familiar today: the mariner's magnetic compass. Of course, there are scholars who argue instead for “multiple independent discovery” origins of the magnetic property of ferrous materials and especially its use at sea, but for the purposes of this article I shall assume it accepted that Chinese mariners were the first recorded users not only of a magnetized pointer, but in particular of one on a ship.³

1. Stephen DAVIES, “The construction of the Selden Map: some conjectures”, *Imago Mundi*, vol. 65, 1, 2013, p. 97-105.

2. A book of coastal views and sailing directions in the Sterling Memorial Library at Yale University (the work is not in the electronic catalogue but has the call no. Covers 56[cea] +1840, “A book of Chinese sailing charts, captured from a Chinese trading junk in 1841”). Stephen DAVIES, “Contrasted perceptions of maritime space in the mid-19th century: The Yale Maps and Western hydrography”, paper given at The Oceans, Consciousness of Space and Cultural Interflow: The Second International Symposium of Cartography, Academia Sinica, Taipei, 2012.

3. For an excellent overview see Barbara M. KREUTZ, “Mediterranean contributions to the medieval mariner's compass”, *Technology and Culture*, vol. 3, 1973, p. 367-383. An interesting contribution

My interest here, provoked by the Yale Maps and especially by the Selden Map with its highly unusual, indeed unique deployment of a Chinese compass rose, is in a variant of what is sometimes called the Needham Question: briefly for the purposes of this article, why did not China come up with a compass that was as useful for marine navigation (in its technical sense) as the mariners' compasses that, by the 17th century, were in wide use in Western ocean going ships?⁴ Derivative from that question, which I shall show raises an important issue as to what, actually, the magnetized pointer aboard Chinese ships was for, is the intriguing puzzle of how pre-western contact Chinese navigators went about their business, especially the linked requirements of knowing the required course to steer (the direction in which one must head to get to where one is going) and then maintaining direction – a steady course – at sea.

The technical problem underpinning the key issue of whether traditional Chinese navigation was compass based can be simply expounded. Within a century or so of each other, both Chinese and western maritime cultures set out to sea with weakly magnetized or magnetizable thin pieces of iron or steel supported by a raft of some sort floated in a bowl filled with water. These serve to give at least some sort of clue to the orientation of the north/south line in relation to the ship's head and hence, if they worked, to a desired direction.⁵ Sometimes, indeed as we shall see rather

to the “whose Daddy got the first car” argument is John B. CARLSON, “Lodestone compass: Chinese or Olmec primacy? Multidisciplinary analysis of an Olmec hematite artifact from San Lorenzo, Veracruz, Mexico”, *Science* 5, Vol. 189, n° 4205, 1975, p. 753-760.

4. “The essential problem [is] why modern science had not developed in Chinese civilization (or Indian) but only in Europe.” This question can be understood to derive from a second one posed by Needham, “why, between the first century BC and the fifteenth century AD, Chinese civilization was much more efficient than occidental in applying human natural knowledge to practical human needs”. See Nathan SIVIN, “The Needham Question”, Oxford Bibliographies at <http://www.oxford-bibliographies.com/view/document/obo-9780199920082/obo-9780199920082-0006.xml>, 2013, accessed on 20.4.2018. Puzzle, paradox and problem are also used. See Patrick K. O'BRIEN, “The Needham question updated: a historiographical survey and elaboration”, *History of Technology*, vol. 29, 2009, p. 7-28.

5. Recent work on the Viking sunstones makes the point that even in customarily overcast conditions, a magnetic compass need not be the sole recourse, see Ramón HEGEÜS, Susanne ÅKESSON, Rüdiger WEHNER and Gábor HORVATH, “Could Vikings have navigated under foggy and cloudy conditions by skylight polarization? On the atmospheric optical prerequisites of polarimetric Viking navigation under foggy and cloudy skies”, *Proceedings of the Royal Society A*, vol. 463 n° 2080, 2007, p. 1081-1095; Guy ROPARS, Gabriel GORRE, Albert LEFLOCH, Jay ENOCH and Vasudevan LAKSHMINARAYANAN, “A depolarizer as a possible precise sunstone for Viking navigation

often, such a rudimentary instrument almost certainly did not work for reasons and causes we understand today but that at the time may have seemed capricious or mysterious. I shall suggest that the result was that the magnetic pointer may have gained and then retained a mystical/magical status requiring the services of an initiate, who alone might be the vector through whom the gods or animating spirits of the magnetized pointer would deign to ensure its compliance.

For reasons or causes that are conjectures, though fairly obvious once we consider North Atlantic tides and weather and, later, the long-distance voyaging out of sight of land across or up and down the Atlantic that began in the 15th century, in the western maritime world this original recourse proved inadequate. Slowly changes were made to take the idea of a N/S direction seeking magnetized pointer, make it more mechanically reliable (+100 years) and adapt it better to use at sea (+200 to +800 years). But in the Chinese maritime world – at least before the Qing Dynasty – this did not happen.

Why not?

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We have no reason to imagine that medieval and early modern Chinese mariners were not in every way the maritime equal of their Western peers in inventiveness, imagination, shipwrighting, sailmaking, seamanship, or navigation any more than we have when considering other non-Western maritime traditions. It would seem to follow that any answer to the question about the relationship between a technically primitive, embarked magnetic pointer and traditional Chinese navigation is to be found in *how* the mariners of the Ming Dynasty and earlier navigated and *what* routes they followed. For if the manner of their voyaging and navigation was such as to lead to few demands for directional guidance from the magnetized pointer then, unlike in the western case, any motivation to improve its performance would have been slight or non-existent. Why spend time

by polarized skylight”, *Proceedings of the Royal Society A*, doi: 10.1098/rspa.2011.0369 published online 2 November 2011 and Bernáth BALASZ, Alexandra FARKAS, Dénes SZAZ, Miklós BLAHO, Ádám EGRI, András BARTA, Susanne ÅKESSON and Gábor HORVATH, “How could the Viking Sun compass be used with sunstones before and after sunset? Twilight board as a new interpretation of the Uunartoq artefact fragment”, *Proceedings of the Royal Society A* 470 20130787; DOI: 10.1098/rspa.2013.0787, 2014.

and effort improving something you do not much use and that does what you want it to do on the comparatively rare occasions when it is turned to, even if sometimes it fails and even if you do not really understand why it works or does not work? As important therefore, why would something needed and used only *in extremis* ever become “demystified” and rendered just a workaday tool needing no divine assistance, just a bit of inventive tinkering?

This then brings us to the conspicuously absent elements in the story of the Chinese compass. First, had Chinese navigators been as dependent on the compass for navigation as is often claimed, Chinese mariners would have become aware of the shortcomings of the tool they found themselves increasingly relying on, they would have come up with fixes and there would have been commentary that reflected such growing awareness and that described the steps that were taken in response. There should also have been discussion of specific, shipboard effects on magnetic compasses – deviation and inclination, or dip – and speculation as to its causes.⁶ There should also exist some residual artefactual trail – surviving whole or part compasses from the Sung through Qing Dynasties or depictions or descriptions of such instruments – pointing to what sort of practical responses were made. In what follows I shall provide a reasonably definitive explanation for why such elements are absent in the story of the Chinese compass.

First, as some reflection on the normal trading routes of Chinese vessels suggests, their navigators were generally dealing with relatively short legs between known waypoints where their position could frequently be visually checked within the limits of the circle of probable error (CPE) of pre-modern navigation.⁷ Few legs of any of the multiple routes we know

6. Variation (as mariners call it) or deviation (as astronomers and geographers call it) is the difference between true north (the direction of the geographical North Pole from where one is) and magnetic north (the direction of the north magnetic pole from where one is). Deviation (for mariners) is a local disturbance to the Earth's magnetic field caused by the ship and its fittings. Dip, which changes according to where one is on the Earth's surface, is a function of the changing inclination of the Earth's magnetic field to the horizontal; its effect on a compass needle is to incline it from the horizontal.

7. The CPE to which traditional Chinese (and other) navigators will have worked was the visual horizon from the upper yard. In the clear air of yesteryear, assuming the object being seen was 20-700 m above sea level, that was about 30-60 nautical miles in radius shrinking, when in known coastal waters to <5 miles, S. DAVIES, “Contrasted perceptions of maritime space”, *op. cit.*

existed were out of sight of land for more than a few hours or, when they were, were so for much more than a day (say <100 miles). Indeed the very format of the Yale Maps with its dependence on coastal views asserts this mainly coastal route-based navigational world. The exceptions, of course, were the two major Indian Ocean routes from the northern entrance to the Malacca Straits to Sri Lanka and from India to the Gulf. The former (c.800 nautical miles) – an almost perfect example of latitude sailing along c.6° N – explains itself. The latter, assuming Quilon (奎隆, today Kollam) to the headland at Ras Al Hadd, could have kept the Indian west coast in sight as far north as today's Dwarkar, north-west of Diu, whence again it was a matter of latitude sailing c.500 nautical miles along 22.3° N. The additional distance in the latter case is around 100 miles, or a day's sailing in a favorable monsoon. In both cases high land behind the landfall would have been identifiable more than a day's sailing away. But even before the Ming withdrawal from Indian Ocean voyaging, these passages would never have represented more than a small fraction of pre-Qing overseas voyaging, so even had they revealed shortcomings with the magnetic pointers, the vast majority of users would have been left unconcerned.⁸

Within the China Seas on the longest legs – Quanzhou to Cape Bojeador (500 inm), the Pearl River to Cape Bojeador (400inm) or Vietnam to NE Borneo (650 inm) – there were cross course checks typical of non-instrument, non-compass dependent navigation. Birds and clouds over Pratas Reef (東沙群島, Dōngshā Qúndǎo) offer a cross course and cross-track error check 150inm out of the Pearl River. The high mountains of Luzon offer a similar pre-arrival check 100 or more miles out from Cape Bolinao. High land (Taiwan, North Luzon) would have been visible (especially at sunrise or sunset) at similarly useful cross course checkpoints on the route from Quanzhou/Zhangzhou to Cape Bolinao. A simple intervisibility calculation will show that an island like Pulau Condore (Côn Sơn Island), with its maximum height of 515.1 m, when viewed from the mainyard of a 30 m junk, thus from some 20 m above sea level, can be seen at 50 nautical miles in good visibility. Higher land can be seen at 100 nautical miles or

8. Geoff WADE, "Chinese engagement with the Indian Ocean during the Song, Yuan, and Ming Dynasties (tenth to sixteenth centuries)", in Michael PEARSON (ed.), *Trade, Circulation, and Flow in the Indian Ocean World*, Basingstoke, Palgrave Macmillan, 2015, p. 55-81, makes this point clear.

more – in extremely good visibility sightings at distances of over 200 nautical miles have been recorded.⁹

Second, Chinese trading was carried on in waters in which, for the most part, the sky is seldom overcast (fewer than 5% of days with 10/10ths cloud) and visibility (especially in earlier, less polluted days) excellent.¹⁰ That means both the sun during the day and the stars at night would have been visible for much of any voyage assuming long-established practices and weather lore enabled well-chosen departure dates during the south-west monsoon. For navigators who used both sun and stars – and we know that Chinese seafarers did – these are generally good to excellent conditions and to a pre-modern navigator make a steering compass redundant.

Third, Chinese trading was seasonal, conducted to coincide with the changing monsoon. Monsoon winds have a high degree of constancy of pattern over any given ten-day period. At an average voyage speed, which analysis of various Chinese sources suggests varied between 2.5 and 6 knots,¹¹ even the slowest 200 inm passage would only take three and a half days. A 650 inm passage, the longest single passage on the Selden Map for example, would take at most 11 days (2.5 kts average) and more probably 6-7 days (4-5 kts average). Even the slowest passage is still quite close to the basic sequence of the NE Monsoon weather pattern. The seas and swells the monsoons generate exhibit a similar constancy. Highly sensitized and experienced mariners, of the kind the typical junkmaster and junk navigator would have been, would have used such directional clues constantly in the course of any voyage, cross-checking them against each other. It would only have been in what would probably have been rare cases of significant disorientation caused by fog or storm that some other, artificial aid like a magnetic pointer may have been required not for course keeping or direction finding but for reorientation.

Put together these aspects of Chinese voyaging make the need for a reliable, auxiliary direction-indicating and steering device a low priority. If we assume a maximum leg of any route that was not pure latitude sailing and

9. Navigating by traditional means to the Philippines the author has sighted the mountains of Luzon at dawn when over 100 miles from landfall. For doubters, see Andrew T. YOUNG, "Distance to the horizon" at http://mintaka.sdsu.edu/GF/explain/atmos_refr/horizon.html accessed on 28.4.2014.

10. Stephen DAVIES and Elaine MORGAN, *Cruising Guide to Southeast Asia*, vol. 1, St Ives, Imray, Laurie, Norie & Wilson, 1996, part 1, Planning Guide, Weather.

11. S. DAVIES, "The construction of the Selden Map", *op. cit.*, p. 99.

had no locational reference for 300 inm, and if we also assume all the other direction indicators used in traditional navigation are helping, an error in mean course steered will seldom if ever be more than 15^0 and usually between 5^0 and 10^0 . It follows that at the end of that leg of the voyage, at most a ship will be 70 miles to one side or the other of its destination and most often more like ± 30 inm.¹² Navigation assisted by early forms of the magnetic steering compass was not conspicuously more accurate, as the fate of Admiral Shovell and his 17th century CE fleet attests.¹³

In short, as I tried to understand the cartographic and related materials before me, I faced a significant question about the assumptions that are normally made as to the meaning of the directional data they contained. Were “needle paths” (*zhenlu*, 針路) indeed what they have always been assumed to be? That is, the familiar, present-day compass course indicated by the needle, or pointer of a magnetic compass? If they were not, then what were they about? The following analysis of traditional navigation in other non-Western cultures and of the magnetic direction indicator carried aboard Ming Dynasty junks in the light of the known history of the technology of the magnetic compass, combined with some careful thought about traditional Chinese navigational materials, suggests that there may be aspects of traditional Chinese navigating that an undue emphasis on a possibly exaggerated interpretation of this very early and dubiously reliable instrument has obscured.

12. For the credibility of this estimate see David BURCH, *Emergency Navigation: Find Your Position and Shape Your Course at Sea even if Your Instruments Fail*, 2nd ed., New York, McGraw Hill, 2008 – what takes Burch 259 pages to explain to we trained instrument navigators would have been second nature to the Chinese navigators with whom we are concerned. See also David LEWIS, *We the Navigators: The Ancient Art of Land-Finding in the Pacific*, 2nd sub-ed., Honolulu, University of Hawaii Press, 1994 and for excellent present day narratives the website of the Polynesian Voyaging Society (<http://pvs.kcc.hawaii.edu/index.html>) especially the pages on wayfinding (ho’okele) accessed 28.4.2014.

13. William E. MAY, “The last voyage of Sir Clowdisley Shovell”, *Journal of Navigation*, vol. 13.3, 1960, p. 324-332; John E.D. WILLIAMS, *From Sails to Satellites: The Origin and Development of Navigational Science*, Oxford, Oxford University Press/Royal Institute of Navigation, 1992, esp. chapters 4 and 9; and Francis R. MADDISON, *Medieval Scientific Instruments and the Development of Navigational Instruments in the xvth and xvth Centuries*, Coimbra, Agrupamento de Estudos de Cartografia Antiga 30, 1969.

When is a magnetic pointer a compass?

The critical distinction between what for the purposes of this discussion I designate a magnetic pointer and a steering compass comes down to their relative useability as navigational aids. This takes us to a key question. What are the essential elements of a reliably usable steering compass? Unless we understand the answers, we are in no position to make any valid claims about compass assisted navigation in any culture at any time.

The development of a wholly reliable, accurate magnetic compass for use at sea as a wholly trustworthy direction finding, steering and position finding aid is the product of three interacting demands. There must be an adequate understanding of the directional properties of the Earth's magnetic field in three-dimensions through time. Second, there must be an understanding of the local shipboard effects of these properties, and this must be widely enough spread amongst users, such that they are aware of how the effects interfere with the performance of a compass and how these may be compensated for. Finally, there must be a resultant compass technology that can reliably and accurately use the directional properties of the Earth's magnetic field to enhance direction keeping and position finding *in a ship at sea*. This does not deny the usefulness of a magnetic pointer in an intermediate state up to a fully developed and understood steering compass, during a period when purely practical "tweaks" preceded any real theoretical grasp of geomagnetism. However, it does assert a developmental continuum from "usefulness only for reorientation *in extremis* and with good fortune" through various improved levels of helpfulness in steering and the identification of landmarks to a reliably useful navigational aid in all conditions.

Meeting all the requirements is exacting but necessary for the compass-based navigation that had become commonplace in western voyaging by the end of the 17th century. A full technical response to the effects of Earth and shipboard magnetism on a magnetic pointer sufficient to turn it into a fully reliable navigational compass was nowhere fully provided until well towards the end of the 19th century. Magnetic pointers went to sea in China in the second decade of the 12th century CE, very possibly before. In Europe they were at sea by the end of the same century, probably

copied from China, perhaps not.¹⁴ But extensive development was needed for the water-bowl and floating needle magnetic pointer, thought to have been used at sea by all 12th and early 13th century users, to begin to become helpful as a regularly used navigational aid, as opposed to an infrequent recourse in an emergency.

The first step was the discovery of the dry pivot (c.1260 CE).¹⁵ Usability was enhanced when the dry pivot needle was fixed to a rotating compass card (c.1380 CE) and given a lubber line (c.1410 CE). But even with the addition of gimbals (before 1500 CE but not comprehensively used until the mid-17th century),¹⁶ accuracy to better than $\pm 10^0$ was the exception rather than the rule.¹⁷ By the end of the 17th century in Europe sufficient progress had been made for something approaching what we can call a magnetic mariner's compass to be contributing to significantly accelerating improvements in navigational and hydrographic accuracy and, as a result, to a virtuous feedback loop.¹⁸ Before that date, magnetic pointer induced failures are as frequent as compass aided success, although by the

14. On both the date of the earliest Chinese magnetic pointer at sea and the actuality and path of transmission of that technology to the west there is uncertainty. Dates as early as the 8th century are possible for the first. For the second, the best thought to date is of a probable borrowing, but with no evidence of date, path or persons save possibly overland via Persian astronomers and then onwards into Europe and thence to Arab seafarers. For a good brief discussion see Dieter KUHN, "Reflections on the current state and significance of the history of East Asian technology", *East Asian Science, Technology and Medicine*, vol. 25, 2006, p. 9-26, p. 13, fn. 16.

15. A good summary of early development, especially in relation to Arab uses is Petra G. SCHMIDL, "Two early Arabic sources on the magnetic compass", *Journal of Arabic and Islamic Studies*, vol. 1.4, 1996-97, p. 81-132.

16. The device was described by Philo of Byzantium (c.280-c.220 BCE), see Michael J.T. LEWIS, *Surveying Instruments of Greece and Rome*, Cambridge, Cambridge University Press, 2001. It was known in China certainly by c.180 CE and possibly as early as 150 BCE, see Joseph NEEDHAM, Gwei-djen LU and Ling WANG, *Science and Civilization in China: vol. 4, Physics and Physical Technology; Part 2, Mechanical Engineering*, Cambridge, Cambridge University Press, 1971, p. 233-234.

17. B.M. KREUTZ, "Mediterranean contributions to the medieval mariner's compass", *op. cit.*, p. 372-373 and Frederic C. LANE, "The economic meaning of the invention of the compass", *American Historical Review*, LXVIII.3, 1963, p. 605-617.

18. For an interesting discussion of 'inflection points' that result from the exponential development of a technology with adequate feedback see Eric BRYNJOLFSSON and Andrew MCAFEE, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, New York, WW Norton, 2014 especially chapters 1 and 2.

beginning of the 17th century successes were increasing rapidly.¹⁹ Only towards the end of the 18th century were the final stages reached – better needles, improved understanding of variation and deviation – that helped achieve the goal (c.1780 CE).

We can say that the development of the magnetic pointer into a useful navigational instrument was a long and laborious exercise in trial and error that took over half a millennium. From the first magnetic pointer in use at sea in China (c.1100) to an instrument used in western vessels that could act as an occasional aid to course keeping (c.1380) nearly two centuries elapsed. For that instrument to become a more user-friendly steering aid (>1410) took a further generation.²⁰ For it to become reliably precise in a range of navigational and seamanship roles in all conditions at sea on any vessel and an essential instrument in the navigator's tool kit took a further four and a half centuries (mid-19th century). In the early 20th century, after nearly eight centuries, genuinely excellent and exact, narrow or dead beat,²¹ liquid filled magnetic compasses were becoming common just as they were superseded by the gyro-compass.²²

The evidence suggests that the only magnetic pointer in use at sea in China, until the adoption in the 16th century, via the Japanese, of a European derived, ungimballed, dry pivot compass without a lubberline, was an instrument with a weakly magnetized, multi-pole needle floating on the surface of a bowl of water, subject to the potentially extreme and increasing

19. By the beginning of the 17th century Dutch compasses, although without gimbals, were sufficiently accurate for regular observations of magnetic variation to be made, on dead-reckoning voyages from the Cape to the Sunda Strait, in an attempt to use change in variation as a means of finding longitude. I owe this point to Nicholas Burningham.

20. Commandant L. DENOIX, "Les problèmes de navigation au début des grandes découvertes", in Michel MOLLAT, Paul HEINSIUS, J. ZOUTIS, and M. MALOWIST (eds), *Le navire et l'économie maritime du Nord de l'Europe du Moyen-Age au XVIII^e siècle*, Paris, SEVPEN, 1960, p. 135.

21. The 'beat' of a compass is the angle and period of oscillation either side of the N/S line. Very poor compass design can lead to an amplifying beat (the needle swings more and more widely until it rotates). Early designs had a wide (>±60°), slowly diminishing beat. Good designs have a narrow (<±5°), rapidly cancelling beat. The best compass has a 'dead' or zero beat.

22. William E. MAY, "The birth of the compass", *The Journal of the Institute of Navigation*, vol. 2, 1949, p. 259-263 and more generally Henry L. HITCHINS and William E. MAY, *From Lodestone to Gyro-Compass*, London, Hutchison, 1952. See for the gyrocompass Jobst BROELMANN, "The development of the gyrocompass – inventors as navigators", *Journal of the Institute of Navigation*, vol. 51.2, 1998, p. 267-273.

oscillations known technically as an “amplifying beat”.²³ Without evidence that our three demands were in the process of being met, such that a magnetic pointer was becoming a compass, it seems proper to conclude that for Chinese navigators, pressures to improve magnetic pointers had not been and, for most traditional junk navigation through until possibly as late as the early 20th century, were not being felt. For that reason we need to reconsider what the contribution of such an instrument could have been to Chinese navigation in earlier times. If the evidence suggests it may have been slight, we must then address the question of what the main sources of direction finding and direction keeping for traditional Chinese navigators were.

Traditional Chinese magnetic pointers and “needle paths” (Zhenlu, 針路)

It is now apposite to turn to the instruments that were used by China’s mariners in their wide-ranging voyaging in Asian Seas, to assess the extent to which they were genuinely useful and frequently used navigational tools and what the use was to which they were normally put. In the light of that assessment, we shall then consider the meaning of the written navigational material in Chinese in known sources.

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The instrument

No one knows with any certainty what any pre-Qing magnetic pointers that were used at sea were actually like. There are hints and loosely formulated descriptions. There is nothing like a working drawing or exact specification. There is no surviving example or indicative surviving part of one. The consensus seems to be that they were probably based on a water-filled bowl on the surface of which a magnetized needle was floated. This is likely most often to have been a simple steel needle thrust through a raft made of rice straw, cork or wood, though more sophisticated floating needles are

23. Joseph NEEDHAM, *Clerks and Craftsmen in China and the West*. Cambridge, Cambridge University Press, 1970, p. 243-244. Mr Tam KL has suggested that the most developed Chinese water compasses used bowls floating within bowls floating within bowls. this does not, because it cannot, overcome the key problems and in any case there is no evidence of any such instrument ever having existed.

recorded. The needle is likely to have been magnetized either by thermoremanence or by being stroked with a piece of magnetite.

The needle itself will have been marked in some way so that the polarities of each end (N & S) were distinguished. We do not know how this was achieved save in the cases where reference is made to encasing them in wooden turtles/fish, the “heads” of which pointed south, because that was the defining direction as the Chinese name “south pointing needle” (指南針) shows.²⁴ With a needle through a raft of straws or cork the marking would probably have been done with a dab of colour, an asymmetry in the raft’s shape or color, or some such. The bowl itself either carried the markings of the initially 12, later 24 point Chinese compass rose around the rim, or it rested on a board with the rose marked on it. That is, the needle rotated independently of the compass rose markings.

It is unlikely this would have been used by the helmsperson, who would rather have been focused on steering a steady course. The pointer would have been called into play by the navigator to check orientation. This would not have been easy in any sort of seaway in which, as the navigator tried to balance himself and keep the bowl steady, the surface of the water in the bowl would have been rolling from side to side in response to the ship’s roll, and from front to back in response to pitch and scend. Worse, as the vessel yawed, if the yaw was of any magnitude, the needle will have begun swinging about. Carrying a full glass of water across a level floor often results in spillage so imagine the task when the floor is pitching, rolling, yawing, heaving, swaying and scending.²⁵ A skilled navigator would no doubt have derived some sort of a mean direction by inspection. Accuracy better than $\pm 20^\circ$ would barely have been possible, but knowing where south lay to within less than a quadrant would have been good enough for re-orientation.

We have seen that the pre-Qing Chinese magnetic pointer is not likely to have been a reliable navigational instrument. As Eric Ash puts it in relation to the very similar early European compass,²⁶

24. For a fascinating discussion of the use of the “south pointing needle” descriptor, and of that needle’s use in the Western tradition, see Eva G.R. TAYLOR, “The South-Pointing Needle”, *Imago Mundi*, vol. 8, 1951, p. 1-7.

25. For these terms of art see the section below *The ship’s motions*.

26. Eric H. ASH, “Navigation techniques and practice in the Renaissance”, in David WOODWARD (ed.), *History of Cartography*, vol. 3, *Cartography in the European Renaissance*, Chicago, University

“ The first compass was little more than a magnetized needle piercing a piece of cork or straw floating in a bowl of water, in which the needle was free to spin toward the north. Such a device, however, would have been of very limited use at sea aboard a pitching and rolling ship.

In short, the Ming Dynasty compass as described was almost certainly impossible to use for course keeping and would have been a very poor tool for direction finding in any conditions but a flat calm. Even in a flat calm its directional reliability is likely to have been poor, thanks to the iron fastened construction of traditional junks and the lack of understanding of deviation, shared with almost every contemporary mariner in the world, that the iron fastenings would have imparted, exacerbated by regular mistakes about placing iron and steel objects (cargo, swords, keys, knives, etc.) close to the compass. As W.E. May notes, citing Cook's own narrative and Bligh's *Bounty* log,²⁷

“ Captain Cook kept the keys of the leg irons in his binnacle, while Captain Bligh thought his binnacle a suitable stowage for a pair of pistols.

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These were some of history's most eminent navigators. Why should we suppose run-of-the-mill navigators of China's working craft any different?

The water-bowl magnetic pointer in use

It seems unlikely that skilled mariners of great experience, who had prosecuted long offshore voyages with success for generations would normally have relied on any so dubious a device for conducting their voyages. For steering and normal navigational work they would have looked to tried and tested methods, relying on them entirely until, as a result of stress of weather, they became disorientated. At that point they would have turned to the promise of their rudimentary pointer. Often it would have done

of Chicago Press, 2007, p. 512. Nicholas Burningham makes the point that to a desperate medieval mariner in dire straits, even something of limited use was better than nothing.

27. William E. May, "Historical notes on the deviation of the compass", *Terrestrial Magnetism and Atmospheric Electricity*, vol. 52, n° 2, 1947, p. 219

what was asked of it – namely provided a sense of north and south.²⁸ Sometimes it would have failed to do so.

Like many a person in the pre-industrial world, especially one engaged in a high-risk activity, a traditional mariner whether European, Polynesian, Indian or Middle Eastern, no matter his skills and experience, will have believed in forces and spirits presiding over his fate. The capricious qualities of this rudimentary magnetic pointer that sometimes came up with an answer and sometimes did not, will have spoken to this way of seeing.

A prayer from the 15th century, attributed to Zheng He, that prefaces what is known as the Laud Rutter (known in Chinese as 順風相送 (*Shunfeng xiangsong*) from its title page) reveals plainly that the compass was a quasi-mystical object the operation of which was, seemingly, subject to divine favour and the correct rituals.²⁹

“O! great guardian spirit generals of the 24 azimuth points of the patriarch of books, *The Compass Classic*, of zi, wu, you, mao, yin, shen, si, hai, chen, qu, chou, wei, qian, kun, gen, xun, jia, geng, ren, bing, yi, xin, ding, gui.

O! Page Boy Who Sets Compass Directions, O! Spirit of the Water Basin, O! Lord of the Changing of the Basin's Water, O! Strong Man Who Puts in Place the Compass Needle, O! Spirit Soldiers Who Move the Compass Needle, O! Guardian Spirits of the Direction of the Needle, O! Master of the Lookout and Patron

28. Nicholas Burningham communicated the following observation, referring to the navigational practices of traditional Indonesia seafarers, based on his wide experience of traditional Asian seaman-ship: “The majority of perahus that made longish voyages carried a compass. It was kept locked in the skipper's sea chest. In 1979 I was sailing from Bulukumba to Pulau Jinato on the overlaid perahu *Harapan Jaya*. It was a horrible dark night with a succession of squalls coming from one direction and then another, and no stars or moon visible. By 0300 no one had any real idea where north was, and we didn't have much of an offing from cliff-girt Pulau Salayar. Nakoda Onseng got his compass out. It was a dry-card compass, though it might once have been fluid-filled, and it was mounted in a rusty enamel mug. He sat it on the deck and watched it for a while. He pointed the direction of north. And then he returned the compass to his sea chest. The idea that a helmsman might look at a compass was entirely absent.”

29. “Zheng He Prayer – *Di luo jingxia zhen shen wen*”, Stephen DAVIES, *Dragons, Waves, Winds, Gods*, Hong Kong, Hong Kong Maritime Museum, 2009. Most of the prayer appears in Louise LEVATHES, *When China ruled the seas: the treasure fleet of the Dragon Throne 1405-1433*, New York, Simon & Schuster, 1990, p. 90. The complete prayer was sourced and translated for the HKMM exhibition by Catalina Chor from Da XIANG (向达), *Liangzhong Haidao Zhenjing* (两种海道针经), Beijing, Zhonghua Shuju, 1961, p. 23-24.

Deity of Carpenters, Luban, O! all of the other immortal masters,
spirit soldiers and divine emissaries.

The divine favour summoned by this invocation could evidently be and obviously had now and then been withdrawn. Sometimes, perhaps more often than would have enabled greater trust to be placed in it for the conduct of voyages, the compass did not do what those using it hoped for. As the prayer invokes in its penultimate trope,

“ Thus we hope and wish that when the compass needle is put in place in the bowl, it will always point true north and south and east and west. That from dawn to dusk the ship’s captain will be protected. That crossing the seas, coming and going, we follow the correct route. That men and ships be both content and at peace. That during our time on the high seas all goes well and is uneventful. That hidden shoals are not met and that the sails are set full forever without worry.³⁰

In his discussion of the *Laud Rutter*, in which he cites the same prayer, Timothy Brook translates the instructions to prepare the compass for use,³¹

“ To fill it with the water on which the needle is set down, it is essential to use *yang* water and not to use *yin* water. What are *yin* and *yang* water? *Yang* water is water that trembles when the wind brushes it. *Yin* water is water that subsides when the wind falls.

Brook confesses himself a bit baffled as to what exactly could have been meant by these gradations of water, hazarding the guess that the distinction may have been between salt and fresh water. He does not even attempt to speculate what the significance of trembling when the wind brushes as opposed to subsiding when the wind ceases might portend. Whatever

30. It has been objected that this belittles Ming Dynasty mariners by making them seem credulous and superstitious dupes. There are two rejoinders. The first is that what today we call superstition was part and parcel of human life everywhere in the 17th century. To observe this is to belittle no one, merely to note a very human response to doubt and ignorance. The second is that, in any case, participating in a ritual that arose from recognizing the unreliability of the pointer (or anything else) does not require a belief in its efficacy. Maybe it will work, maybe it won’t. Even if it never will, in default of any other explanation of the needle’s apparent caprice, why buck habitual practice and disturb shipboard harmony? One could call it a traditional navigator’s version of Pascal’s wager.

31. Timothy Brook, *Mr Selden’s Map of China*, London, Bloomsbury, 2013, p. 102.

the distinction was, that what sailors told the landlubbers wasn't very well understood is made plain by what the rutter tells us comes next,³²

“ Lay the compass base level and orient it towards the south. Then it is necessary to set down the needle pointing to the mansion of Heaven...The mansion of Heaven is the chief of the twenty-four directions. Heaven governs the disposition of calamity, which is why it is necessary to start the needle from there. The needle should then indicate the direction, but don't let it sink.

Brook fails to note that if someone can orient the compass bowl to the south, then he already knows where south is and therefore can presumably have little need for a pointer.

It is important not to ignore the *post hoc ergo propter hoc* fallacy involved in having to know the solution before you can set up the instrument that solves the problem. Brook's naively functionalist assumption is that the apparent semi-religious ritual can be ignored. The idea, he contends, is to ensure that the needle is placed in such a way “to avoid laying the needle in the direction you think you are going,” thereby ensuring a consistent placing of the needle in relation to the N/S line.³³ But, the imponderability of this explanation aside, in order to do what the instruction requires one would need to know in which direction South lay before one started, so that one knew the relative direction of the Mansion of Heaven. It follows that a naively functionalist explanation won't do and we should instead take seriously the thought that the Ming Dynasty compass is to be understood as a religious or quasi-religious object and its use a religious or quasi-religious ritual perhaps turned to when things had gone wrong, not as a matter of daily routine.

In short, this attempt to gloss over the ritualistic nature of the exercise, despite the prefacing prayer and the fact that the pilot and magnetic pointer bosun (火長, *huozhang*) of a junk also looked after the ship's shrine, made sure that incense sticks were always burning and kept the magnetic

32. *Ibid.*

33. Quite what Brook meant by this is not easy to decide, for why would a mariner “lay the needle in the direction (he thinks he is) going” unless the mariner is headed either North or South in which alignment, presumably, he is hoping the needle will end up?

pointer and associated materials in the shrine, seems disingenuous.³⁴ It is perfectly intelligible in the context of such a vernacular navigational system simultaneously to believe that the magnetic pointer might save the ship, as from time to time no doubt such instruments may have done, that it was animated by the gods, or at least mysteriously animated, and that in order for it to work the correct rituals had to be followed and prayers made, and that as a ritual entity it should be kept in the shrine of the gods whose spirits would be needed to animate or to help animate it. Purely technically as we shall see below, if such a magnetic pointer worked, on the sorts of occasion it was likely to be most needed, it probably did so against the odds, so appealing to higher assistance made perfect sense.

To conclude, we can say that the magnetic pointers that we are led to believe were what Chinese seafarers used to assist them in their venture-some and economically important trading voyages were not reliable or even minimally useful steering aids or navigational instruments. Such written evidence as we have seems to suggest that the simple and dubiously reliable instrument was a last ditch recourse, on what must have been the few occasions when everyone was utterly and completely disorientated, that re-orientated them and allowed them again to use their traditional course keeping and locational skills.

Indeed, that the traditional Chinese compass did not work in any other way is strongly suggested by the features of its history we noted in the Introduction. There is the absence of technical improvement. There is the absence of commentary about dip or inclination. There is the absence of commentary about deviation.³⁵ And there is the absence of any remnants or intact examples of improved models. Had the magnetic pointer been

34. T. BROOK, *Mr Selden's Map of China, op. cit.*, p. 94, quoting William Dampier's description of a visit to a Chinese junk from chapter 15 of William DAMPIER, "Introduction", in Sir Albert GRAY, *A New Voyage Round the World*, London, A & C Black/Hakluyt Society, 1937. That the shrine keeper gave his title to the navigator is itself, of course, indicative.

35. Needham's discussion of this issue is distinctly slippery, suggesting that an awareness of the problems of nearby masses of natural magnetic sources like hills or islands with local magnetic anomalies is identical to an awareness of deviation. At a high level of theoretical generalization this is correct. In navigational practice it is quite wrong. Understanding of deviation led to the possibility of correcting a compass for the worst of its effects and tabulating the rest to give adjustments to make for courses steered and bearings taken. For a local anomaly outside the ship no such correction can be made, see Joseph NEEDHAM and Colin A. RONAN, *The Shorter Science and Civilisation in China: an abridgement of Joseph Needham's original text*, vol. 3, Cambridge, Cambridge University Press, 1986, p. 46.

widely used by Chinese navigators for other than occasional reorientation, the skills and observational powers of those very same navigators would have led them to notice, just as they led western seafarers to notice, the factors that were affecting its accuracy. They would thus have begun devising – as their western peers began to devise – “tweaks” to try to deal with the problems. Equally some would have begun theorizing, as did some in the west, about the problems and made efforts to try to understand them. The result would have been a compass, not a magnetic pointer.

Of the points of the compass and the compass needle

Given the unquestioned achievements of traditional Chinese navigators and the *zhenjing* (針經, usually translated as “rutter”) (sailing directory) that have survived, that the Ming Dynasty compass was not a credible navigational instrument and thus was not used as one seems a very bold claim indeed. After all, literally *zhenjing* seems to mean “needle (path) book”.

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This apparent problem may be helpfully dissipated by a common distinction. On the one hand there is the circle of the horizon understood in orientational terms as having cardinal and intercardinal points, all of which long predate the use of a compass needle and are common to almost every culture. On the other there is the Johnny-come-lately of an instrument based on those points using a magnetized needle to indicate the direction of north or south.

In the west as in China, the cardinal directions are amongst the first mental companions to daily life and appear in the earliest known human records millennia before anyone suggests any form of magnetic pointer had been invented.³⁶ Depending on culture these were originally the four (Europe) or five (China,³⁷ Arab, America) cardinal points – North, East, South, West

36. See the luminous discussion in Mircea ELIADE, trans. W.R. TRASK, *The Sacred and the Profane: The Nature of Religion*, New York, Harcourt, Brace & World, 1957, chapter 1, esp. p. 42-47. For the case of China, see Paul WHEATLEY, *The Pivot of the Four Quarters: A Preliminary Enquiry Into the Origins and Character of the Ancient Chinese City*, Chicago, Aldine, 1971.

37. Sarah ALLEN, *The Shape of the Turtle: Myth, Art and Cosmos in Early China*, Albany, State University of New York Press, 1991 prefers the term “quadrates”, see p. 75-77. See also Mark E. LEWIS, *The construction of space in early China*, Albany, State University of New York Press,

and, where there were five, Centre. Come upon astronomically – the Sun rises in the East, is due south at noon (north in the Southern Hemisphere) and sets in the West, the Pole Star is approximately N at night, the zenith is above our heads and the centre at our feet – they were supplemented by other natural indicators like seasonal winds and, with the addition of the four intercardinal points (North East, South East, South West and North West), gave the classic Eight Winds, shared by western, Persian/Arab and Chinese cultures.³⁸

In short, from the very earliest times human beings, mariners amongst them, became accustomed to orientating themselves in terms of directions formed in reference to an imaginary circle delimiting the visual horizon and related to identifiable basic directions derived from naturally occurring phenomena. For everyday purposes on land (with the exception of desert or tundra travel), where paths are seldom absolutely straight, few things in day-to-day travel require directional accuracy much better than eight directions, as in “head north west until you see X”, each separated by 45° from the next. But once the need for greater accuracy arose, steadily the span between the main directions was narrowed. In the west, using the natural human ability accurately to halve spatial dimensions by eye, the horizon was progressively split from four, through eight to sixteen, thirty-two and finally sixty-four parts. From the original eight, however, the Chinese world seems to have taken the extremely unusual step of trisecting the angles between cardinal and intercardinal points.³⁹ The explanation for this can probably be derived from the names of the Chinese compass points, which over time became the names of the hours of the day.⁴⁰

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2006, especially the Introduction, and the helpful discussion in Aihe WANG, *Cosmology and political culture in early China*, Cambridge, Cambridge University Press, 2000, especially the discussion on p. 48-50 of the Shang astronomical techniques of locating True North by bisecting the angle of the directions of sunrise and sunset as well as by the Pole Star.

38. T. BROOK, *Mr Selden's Map of China*, *op. cit.*, p. 103.

39. The classic proof of the impossibility of the trisection of an angle using just straight edge and compasses was provided by the French mathematician Pierre Laurent WANTZEL, « Recherches sur les moyens de reconnaître si un problème de géométrie peut se résoudre avec la règle et le compas », *Journal de Mathématiques Pures et Appliquées*, 1 (2), 1837, p. 366-372. How the Chinese compass rose was accurately constructed seems to be unknown.

40. T. BROOK, *Mr Selden's Map of China*, *op. cit.*, p. 103-104, repeats the ignorant canard about the west having directions in “geometrically clean but arithmetically messy” quarter and five-eighths degree units and praising the “elegant and simple” Chinese system, whilst ignoring the Chinese circle of $365\frac{1}{4}^{\circ}$ (度 *dù*) with its 24 sectors of $15\frac{1}{32}^{\circ}$. See John NORTH, *Cosmos: An Illustrated History of*

This is the signal difference between western and Chinese directional conventions. Namely that the Chinese system of directions is a solar clock that, by the Ming Dynasty, covered all twenty-four hours. The table below, taken from Endymion Wilkinson's invaluable guide to the recondita of the Chinese world, shows how by the Ming Dynasty the compass points measured the passing day.⁴¹

Character	Pinyin	Hr	Dir'n	Character	Pinyin	Hr	Dir'n
壬時	<i>Rénshí</i>	2300	345°	丙時	<i>Bǐngshí</i>	1100	165°
子時	<i>Zǐshí</i>	2400	000°	午時	<i>Wǔshí</i>	1200	180°
癸時	<i>Guǐshí</i>	0100	015°	丁時	<i>Dīngshí</i>	1300	195°
丑時	<i>Chǒushí</i>	0200	030°	未時	<i>Wèishí</i>	1400	210°
艮時	<i>Gènshí</i>	0300	045°	坤時	<i>Kūnshí</i>	1500	225°
寅時	<i>Yínshí</i>	0400	060°	申時	<i>Shēnshí</i>	1600	240°
甲時	<i>Jiǎshí</i>	0500	075°	庚時	<i>Gēngshí</i>	1700	255°
卯時	<i>Mǎoshí</i>	0600	090°	酉時	<i>Yǒushí</i>	1800	270°
乙時	<i>Yǐshí</i>	0700	105°	辛時	<i>Xīnshí</i>	1900	285°
辰時	<i>Chénshí</i>	0800	120°	戌時	<i>Xūshí</i>	2000	300°
巽時	<i>Xùnshí</i>	0900	135°	乾時	<i>Qiánshí</i>	2100	315°
巳時	<i>Sìshí</i>	1000	150°	亥時	<i>Hàishí</i>	2200	330°

Marking the hours by directions, or the directions by hours in the Ming

It thus seems quite probable that traditional Chinese sailors sailed the seas using as their mental reference a solar compass with which they “marked out” their horizon and, using the wind, the run of the sea and other natural clues, maintained their sense of direction. At night this will have been supplemented by the lore of the night sky we know to have been part of the traditional Chinese navigational repertory. Such techniques were used by Phoenician, Classical Greek, Arab, Indonesian and Polynesian navigators

Astronomy and Cosmology, Chicago, University of Chicago Press, 2008, chapter 5 especially p. 138 and Joseph NEEDHAM and Ling WANG, *Science & Civilization in China*, vol. 3: *Mathematics and the sciences of heaven and Earth*, Cambridge, Cambridge University Press, 1959, p. 217, fn. 5.

41. Endymion WILKINSON, *Chinese History: A Manual*, revised and enlarged edition, Cambridge MA, Harvard-Yenching Institute Monograph Series, 2000, chapter 6, p. 198-219.

and, indeed, almost every traditional sailing culture.⁴² It is how many sailors still sail today and, as David Burch shows, as do the voyages of the replica Polynesian voyaging ship *Hokulea*, it still works fine.⁴³ As Gene Amarell points out, traditional Bugis navigators orientated themselves – and still do orientate themselves – using a wind compass and a star compass in addition to their intimate knowledge of the waters in which they sail that allows them meditatively to “visualize” a passage such that they believe they can will their ship’s ability to find its way to its destination.⁴⁴

It follows that what land-based scholars tell us – and as Timothy Brook notes,⁴⁵ virtually all we have about Chinese navigation is in digests and commentaries by land-based literati – is always mediated through the limits of their understanding; more specifically their classical Chinese education and vocabulary. What Chinese sailors called the courses they followed around Asian seas in their vernacular, we have no idea and will almost certainly never discover. They may have called them *zhenlu*, 針路. But it is equally possible they called them nothing of the sort and that *zhenlu* was the best approximation in written language to summarily express something that, perhaps, the land-based redactor himself but barely understood.

Brook quotes the scholar Zhang Xie’s (張燮) *Dong Xi Yang Kao* (東西洋考, Study of the Eastern and Western Seas), published in 1617 in a way that is extremely suggestive of something a lot more like traditional, vernacular navigation than it is compass based navigation.⁴⁶

42. Gerald R. TIBBETTS, *Arab Navigation in the Indian Ocean Before the coming of the Portuguese, Being a translation of Kitab al-Fawa'id Fi Usul Al-bahr wa'l-qawa'id of Ahmad b. Majid al-Najdi*, London, Royal Asiatic Society/Oriental Translation Fund, 1971, p. 119-123 notes that an Arab vessel’s gunwhale was implicitly ‘marked up’, given the course it was steering, with the appropriate heavenly directions. For the Polynesians see LEWIS (1994). For an interesting linking article see Michael D. HALPERN, “Sidereal compasses: a case for Carolinian-Arab links”, *Journal of Polynesian Studies*, vol. 95, n° 4, 1986, p. 441-460.

43. D. BURCH, *Emergency Navigation*, *op. cit.*, also Ben R. FINNEY, *Sailing in the Wake of the Ancestors: Reviving Polynesian Voyaging*, Honolulu, Bishop Museum Press, 2004 and more generally the materials of the Polynesian Voyaging Society at <http://hokulea.org/holokai/> accessed on 25.4.2014

44. Gene AMARELL, *Bugis Navigation*, New Haven, Yale University, Southeast Asia Studies Program, Monograph #48, 1999, chapters 4 and 5. I am indebted to Pierre-Yves Manguin to drawing my attention to this fascinating and pertinent monograph.

45.. T. BROOK, *Mr Selden’s Map of China*, *op. cit.*, p. 90-91.

46. *Ibid.*, p. 94-95.

“ Though the deeps across which he traces his watery course are vast, he is listened to in all things affecting the command of his ship... He knows there are regularities in cloud formations and the movement of the winds, and with this knowledge he ploughs through the waves for ten thousand *li* and is never once fooled into taking the wrong course.

Zhang Xie then goes on to write about the magnetic pointer and its use. Given what we have seen is technically possible, what Zhang writes suggests he has credulously swallowed something very close to a fisherman's story. After all, as Brook elsewhere notes, navigational lore and detail was an extremely closely guarded secret and what he calls “compass manuals” were “never leaked to outsiders.” He notes, “none survives in its original form.”⁴⁷ But despite this he repeats Zhang Xie's credulous and wildly exaggerated encomium about the compass that only someone with a desk jockey's understanding of marine navigation and who had never been offshore in a relatively small vessel in rough weather trying to use a Ming Dynasty water compass could have written.⁴⁸

“ Relying on (the compass, mariners) may grope their way forward in the gloom and yet have complete knowledge of whatever part of the ocean they are in and what dangers they may have to look out for. Indifferent to the storms buffeting them, they remain at ease in their places. Despite sharp winds and crashing waves, they voyage on as if everything were normal. With their long experience at doing this, they sail as though they are walking on level ground. At a glance they can figure out whatever it is they need to know.

The land-based commentator will have known of the water bowl magnetic pointer and its later, slightly more sophisticated dry-point replacement on

47. It is possible that the Yale Maps may indicate what an actual rutter looked like. If so, that would be evidence in favor of the hypotheses advanced in this essay. See S. DAVIES, “Contrasted perceptions of maritime space in the mid-19th century”, *op. cit.*, also Jiang QIAN and Jiarong CHEN, “A Discussion on the Qing Navigational Map Book Kept at Yale University” (〈牛津藏《明代東西洋航海圖》姐妹作—耶魯藏《清代東南洋航海圖》推介〉錢江、陳佳榮), 2013, at <http://www.world10k.com/blog/?p=2382> accessed on 19.5.2014.

48. S. DAVIES, “Contrasted perceptions of maritime space in the mid-19th century”, *op. cit.* For the later terms derived directly from fishermen and called *genglu bu* (更路簿) and *shuilu bu* (水路簿) – presumably what the users called them – see Ulises GRANADOS, “The South China Sea and its coral reefs during the Ming and Qing dynasties: levels of geographical knowledge and political control”, *East Asian History*, n° 32/33. 2006/07, p. 109-128, p. 125.

the still and steady surface of his writing table. He will have been able to see how it pointed the way such that for his mind to conjure an image of a mariner following the needle would have been but a step. It is quite possible that in the process an understandable conflation occurred between the mariner's mental directional points and the actual magnetic pointer in the bowl that was turned to from time to time because everyone had become disorientated and didn't know which way south lay. We shall never know.

However, one of the best-known images of the Chinese compass from the *Zhinan Zhengfa* (指南正法, *The True Art of Pointing South*),⁴⁹ in fact very neatly illustrates exactly the point being made. It could be taken to be a representation of a Chinese compass card of the kind on the rim of the bowl, or on the board on which a compass bowl rested. It could as well be a representation of the division of the observed horizon. That is, it might be serving exactly the same purpose as the wind roses on early European portolan charts that *preceded* the use of the wind rose as a compass card. To those who have also seen the Yale Maps referred to above, it could equally be an excellent crib instructing the use of such a rutter and how the instructions on it were to be read. "Here's how the horizon divides up and how the islands mentioned in the views are located around it."

This sort of "compass rose" is conceptually independent of any artificial means by which directions/bearings may be come upon, as is still the case today with the compass rose on a modern chart. A rose of this sort is a direction-giving or orientating device, not a direction-finding or course-keeping instrument.⁵⁰ A good illustration of what this means, and of how orientating conceptions seem to have preceded and are in any case theoretically independent of magnetized pointers, is found in the development of the European portolan chart.⁵¹

49. ANON, *Zhinan Zhengfa* (指南正法, *The True art of pointing south*), Oxford, Bodleian Library, mid-17th century. Jiarong CHEN (陈佳荣), "《指南正法》完成年代上限新证" (*New Evidence on the Year of Completion of the Zhinan zhengfa*), *National Maritime Research*, vol. 7, 2014, p. 15-19 has recently argued that the work was written in (or possibly after) 1685.

50. D. BURCH, *Emergency Navigation*, *op. cit.*, p. 21-23, "Steering without a compass" specifically notes the usefulness of compass cards as an important orientating device quite independently of a magnetic pointer.

51. Nicolai ROEL, *The Enigma of the Origin of Portolan Charts: A Geodetic Analysis of the Hypothesis of a Medieval Origin*, Leiden, Brill, 2016, introduction and p. 14-15, Silvanus P. THOMPSON, *The*

The means by which a navigator establishes the correct orientation for his mental directional rose does NOT have to be a ship's magnetic, fluxgate or gyro compass. It could be the sun, the Pole Star or a known transit line between visible objects even, if super accuracy was not the issue as in early navigation it was not, the run of a regular monsoon sea or direction of a seasonal wind. Provided the navigator has a clear sense of a circle around his vessel orientated in relation to the source of the prime bearing, he or she can "see" the bearing of whatever it is that is of concern, like the bearing of a danger or course to a hoped-for destination. In the Qing Dynasty depiction of the compass rose with the islands around the horizon from the *True Art of Pointing South* it is exactly that way of seeing that is suggested.

In short there is no necessary relationship between having a directional rose by which a navigator orientates his world and his routes, and having a magnetic pointer. Conceptually these are distinct. Calling routes established by orientations derived from the sun or the stars 'needle paths' does not strictly imply an actual magnetic pointer.⁵² It could be that a traditional Chinese mariner used some cognate term reflecting his intimate familiarity with the way he portioned out his navigational horizon such that the mental idea was of something pointing in each direction, whether the 'ray' of a conceptual directional rose, a finger or a needle.⁵³ We know that exactly that way of seeing was what was involved in the European "winds", as it was with the sidereal 'compasses' with which Arab⁵⁴, Polynesian⁵⁵ and Bugis⁵⁶ navigators directed their paths across what were in some cases rather wider oceans than were habitually tracked by traditional Chinese mariners. Certainly by the late Qing Dynasty, as Granados' work indicates,

Rose of the Winds: the Origin and Development of the Compass-Card, London, Oxford University Press, 1913, p. 4-5, 13-22.

52. This point can be simply made by reflecting on the etymology of 'compass' and one of its meanings today. It began, broadly, as 'to encompass', 'to go around', 'to circumscribe', from which meaning was derived the later word for the navigational instrument.

53. One notes that today *zhizhen* (指針) – the characters of *zhinanzhen* (指南針 or 'south pointing needle') meaning 'pointing needle' can be used to mean the hand of a clock, a pointer on a dial, a cursor on a computer screen – in short any entity that shows the way, as it were.

54. Michael D. HALPERN, *The origins of the Carolinian Sidereal Compass*, unpublished MA thesis, Texas A&M University, 1985, fig. 7, p. 34 also for sidereal compasses from the Carolines, Ontong Java and Madura.

55. Charles O. FRAKE, "A reinterpretation of the Micronesian 'star compass'", *Journal of the Polynesian Society*, vol. 104, n° 2, 1995, p. 147-158.

56. G. AMARELL, *Bugis Navigation*, *op. cit.*

how users described their route guides made no reference to needles, using instead either *genglu bu* (更路簿 roughly book of watch period-measured routes) and *shuilu bu* (水路簿 water/sea route book).⁵⁷

In this context of the Chinese experience, we may accordingly now turn to the matter of what distinguishes between what I am stipulatively identifying here as a magnetic pointer on the one hand and a fully-fledged marine compass on the other.

The problem and its elements

A compass needle at its simplest is merely a length of magnetized ferrous material so mechanically arranged that it can freely pivot to align itself with the local geomagnetic field. Organize something that satisfies that elementary description – a magnetized spoon on a plate, a magnetized needle suspended by a thread of silk, a magnetized needle in a bowl of water buoyed by a raft of rice straw – and one has a needle that, free of nearby sources of magnetic perturbation, will align itself magnetic N/S.

Sadly this “scholar’s study” solution has significant limits to usability, and nowhere more so than at sea. Marine compass design must take on board that a ship is an unstable platform, that the Earth’s magnetic field is three, not two-dimensional, and that other local ferrous material also has a magnetic field. To work in its unstable environment as more than a magnetic pointer working as a momentary emergency recourse, a compass must respond to these perturbations in such a way as accurately to align itself magnetic N/S and stay so aligned in almost all states of wind and sea for the duration of a passage.

The ship’s motions

Unlike a scholar’s study, a ship moves within six degrees of freedom involving three linear motions of translation and three axes of rotation.

The motions of translation are vertical heave, fore-and-aft surge and side-to-side sway. The axes of rotation are front-to-back pitch around the lateral or transverse axis, side-to-side roll around the longitudinal or roll axis

57. U. GRANADOS, “The South China Sea”, *op. cit.*

and side-to-side yaw around the vertical or yaw axis. These are caused by the movement of a ship in a seaway and vary in period (the time between moving from one end to the other of an axis of movement), amplitude (the distance between extremes of movement) and regularity (how closely period and amplitude approximate to periodic motion). Those quanta depend on the sea and swell state⁵⁸ and the size, displacement and point of sail of the ship.

Basically the smaller the ship and the lighter its displacement, the more lively are all six of its motions in any given sea and swell states above zero. Most NE Monsoon voyages in junks on China's coasts in the Ming Dynasty will have been in sea state 4 to 5 (mean wave heights 1.25-4 m) and swell state 4 to 5 (100 m-200 m crest to crest and <2> 4 m trough to crest). It is important to realise that a sea (a movement in the sea surface produced by local weather conditions) and a swell (a movement of the sea surface produced by weather conditions at a distance) are not necessarily, and indeed not often aligned. That is, the mean direction of advance of seas is seldom identical or even particularly close to the mean direction of advance of any swell (of which there may be more than one). The resulting irregular interference pattern of combined sea and swell states is also influenced by the depth of water, any reflected seas or swells from nearby shorelines, and whether any current or tidal stream is flowing with, against or across the run of sea or swell.⁵⁹ Thus a vessel's motion is almost always *irregular* both *within* any period of movement and *between* any two or more movement periods. The results are unequal movements either side of the centrepoint of any given axis and inconsistent amplitudes of movement through time.

It follows that as a relatively small vessel (the average *nanyang* trade Ming Dynasty junk will have been around 30 m loa)⁶⁰ steers through the sea,

58. This is today measured by the twin, 9 state, Douglas Sea State and Swell Scales. The Sea State Scale runs from 0 = Calm to 9 = Phenomenal. The Swell Scale from 0 = No swell to 9 = Confused. See http://www.eurometeo.com/english/read/doc_douglas accessed on 16.4.2014

59. For a recent analysis see Judith WOLF and David PRANDLE "Some observations of wave-current interaction", *Coastal Engineering*, vol. 37, 1999, p. 471-485.

60. It is hard to be exact. Early Qing records suggest that the *Ji-type* Tongan ship was 26 m loa and the N° 1 type Tongan ship 22 m loa (see http://theme.npm.edu.tw/exh102/tongan_ships/en/ch00.html accessed on 17.4.2014). The nine Chinese design vessels in the *Tosen no Zu* from the mid-Qing Dynasty scrolls average 30.6 m loa. See Jun KIMURA, "Principles in East Asian Shipbuilding Traditions", unpublished PhD thesis, Flinders University, 2011, table 3.1, p. 50. These tally with

assuming that there is a quartering or beam wind typical of a standard voyage to or from the nanyang, it will have been lively. Its poop (the back of the vessel where the compass was housed, though possibly not used there) will have been moving in a complex, seldom regular manner covering considerable arcs.⁶¹ Any ship's compass in the aft portion of a junk will therefore have been moving in a vertical arc <4 m top to bottom (a combination of heave and pitch). Depending on height above the hull's centre of gravity, it will have been rolling in a shallow arc <1-3 m from side to side and shimmying as a result of sway. It will also have been yawing – swinging <30° either side of the mean track. It will have been accelerating and decelerating on the fore and aft line as the vessel surged down and up the seas as they rolled through – products of heaving and scending. It is hard to model this movement in your mind's eye, but it will look something like the path of what mathematicians call a strange attractor.

The conclusion must be that any magnetic pointer that is to work effectively as a marine compass must be able to cope with the natural motion of a ship in a seaway both in normal and in extreme conditions.

Steering a ship

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Steering a sailing ship in a normal offshore sea is a delicate combination of movements somewhere between riding a horse and flying. The result is never a straight line but instead a sinuous but irregular progress in a general direction.

The movement of a ship under sail at sea in anything other than a flat calm is complex and presents the helmsperson with a task requiring experience and skill as various interacting forces combine to push the ship off the straight-line course she or he is trying to steer.

As the ship moves forwards, so the bow swings from left (port) to right (starboard) by 15° to 30° or more either side of the intended track depending on the sea state and the skill of the helmsman. As the ship's head swings one way or the other, so the rate of swing accelerates and then decelerates. Skilled helmspersons smooth this constant alteration in the

Osamu OBA, trans. Joshua VOGEL, "Sino-Japanese relations in the Edo Period, part ten: on the matter of vessels sailing to Japan", *Sino-Japanese Studies*, vol. 12.2, 2009, p. 56.

61. Which is at least one reason why many people get seasick.

ship's head, keeping its amplitude to a minimum, averaging the best course they can.⁶² As the ship's head begins to swing, so a counteracting amount of rudder is applied to 'meet' the swing. It is eased as the ship responds and rapidly removed before the ship over-corrects in the opposite direction. Less skilled helms tend to be clumsy. Any steering system with much slack in the rudder's control system or with much friction to overcome – in general the condition of most pre-19th century shipping and all traditional Chinese shipping⁶³ – makes the helmsperson's difficult task more so. The result will be greater and more erratic movement of the ship's head and hence, if ideally, require a fast-responding magnetic pointer with minimal lag and overshoot.

Ship's magnetism

A compass is mounted in a ship. Two things about this can affect accuracy. The first is the location of and angle to the horizontal plane of the compass in relation to permanent or temporary magnetic fields on board the ship whether they are made of iron or steel or, if made of wood, have enough iron and steel fastenings and fittings to present a problem.⁶⁴

The 16th century CE *Longjiang chuanchang zhi* (龍江船廠志) points out that a 30m long ship required at least 750 kg of iron (nails and ironwork, >70% nails) to build.⁶⁵ Prof. Shiba Yoshinobu confirms this by noting that in Song times a vessel was constructed using 3,685 nails for every

62. This is an important reason for the western invention of the traverse board, the intention of which was to ensure that the varying courses averaged over each hour of a watch could be recorded such that, later, along with an hourly recorded speed record, the navigator could derive an average steered over the whole watch. The first traverse boards are thought to have been in use by around 1500 CE – see Gerard L'E TURNER, *Scientific Instruments 1500-1900, an Introduction*, London, Philip Wilson/University of California Press, 1998, p. 35. No Chinese equivalent has yet been identified.

63. Stephen DAVIES, *East Sails West: The Voyage of the Keying 1846-1855*, Hong Kong, Hong Kong University Press, 2014, p. 95-98 and Stephen DAVIES, *Coasting Past: The Last South China Coastal Trading Junks Photographed by William Heering*, Hong Kong, Hong Kong Maritime Museum, 2013, p. 99-111.

64. W.E. MAY, "Historical notes on the deviation of the compass", *op. cit.*

65. Sally K. CHURCH, *Nanjing's Longjiang Shipyard Treatise and Our Knowledge of Ming Ships*, Civilizations in Contact, Faculty of Asian and Middle Eastern Studies, University of Cambridge, Funded by the Golden Web Foundation, (Forthcoming), n.d., kindly made available to me by Dr. Church.

100 picul capacity.⁶⁶ To get that in perspective, GRG Worcester noted that a Ningbo iceboat that had a capacity of 100 piculs was 21.33 m loa, 4.6 m beam and 2.44 m moulded depth.⁶⁷ So a nanyang trader 30 m loa, 6m beam and 3.2 m moulded depth would have had 7,000-8,000 iron nails each weighing >150 grams or c.1.125 tons of iron. That meant some 230-265 nails (34.5-39.75 kg) fairly symmetrically placed in hull and bulkheads for every meter of the hull's length. In addition, we know both from historical records and from various South China Sea wreck excavations that the carriage of scrap iron and other iron as cargo was common.⁶⁸

Over one ton of iron symmetrically placed throughout a vessel's hull all magnetized to a common polarity by being hammered into place whilst the ship was on the building ways in a fixed orientation to the Earth's magnetic field would inevitably have had a magnetic signature, albeit a relatively slight one.⁶⁹ In terms of ship's magnetism this is known as the ship's permanent magnetism. The iron in a ship and any in its cargo also has what is known as induced magnetism caused by the Earth's magnetic field that varies as the location and course of the ship vary. The resultant deviation of the compass (an effect additional to variation) can be very large.⁷⁰ For example late 18th century Royal Navy sailing masters had an allowance called 'in draft', which they added or subtracted from the ship's heading by compass to get a more accurate sense of where the ship was

66. Yoshinobu SHIBA, trans. Mark ELVIN, *Commerce & society in Sung China*, Michigan Abstracts of Chinese and Japanese works on Chinese history n° 2, Ann Arbor, Michigan, Centre for Chinese Studies, University of Michigan, 1970, p. 93.

67. George R.G. WORCESTER, *The Junks and Sampans of the Yangtze*, reprint, Annapolis, Naval Institute Press, 1971, p. 176.

68. Michael FLECKER, "Maritime archaeology in Southeast Asia", in John MIKSIC (ed.), *Southeast Asian Ceramics: New Light on Old Pottery*, Singapore, Southeast Asian Ceramics Society, 2009, p. 34-47, esp. the Java Sea wreck, p. 40, Michael FLECKER, "The South-China-Sea Tradition: the Hybrid Hulls of South-East Asia", *International Journal of Nautical Archaeology*, vol. 36, n° 1, 2007, p. 75-90 for the Royal Nanhai wreck and Kwa-chong GUAN, "Locating Singapore on the Maritime Silk Road", *Nalanda-Sriwijaya Working Paper Series*, n° 10, 2012 for the Java Sea, Intan, Pulau Buaya, Turiang, Brunei and Binh Thuan wrecks.

69. William WALKER, *The Magnetism of Ships and the Mariner's Compass, Being a Rudimentary Exposition of the Induced Magnetism of Iron in Sea-Going Vessels and its Action on the Compass in Different Latitudes and Under Diversified Circumstances*, London, Piper Bros. & Co., 1853, p. 40, 174

70. It is important for those unfamiliar with the technology of the sea to understand that deviation and variation are two DIFFERENT phenomena, if in doubt see fn. 6 above.

actually pointing. “In draft” could be as much as two points (22.5^0) and sometimes more.⁷¹

The first known record of someone noticing these effects was in 1538-1539, by João de Castro (1500-1548), a Portuguese navigator.⁷² It was regularly noticed and commented on thereafter though not, as far as the record indicates, outside Europe. Meanwhile extensive observation began, all of which, most importantly, encouraged increasingly comprehensive data collection. By 1794, the first proposal to create “deviation cards” by swinging the ship was made by John Churchman⁷³ and, following work by William Scoresby (1759-1857) and Matthew Flinders (1774-1814) a decade or so later, the beginning of a practical understanding of deviation had begun.⁷⁴

The Earth’s magnetic field

A compass is in principle a simple bar magnet that aligns itself with the local geomagnetic field. The field is conventionally represented as having two components: horizontal and vertical.⁷⁵

At any one point on the Earth’s surface the compass needle will align itself with the resultant of the two components. On a scale of 0 to 1, at the magnetic equator the horizontal component is 1 and the vertical component zero

71. J.E.D. WILLIAMS, *From Sails to Satellites*, *op. cit.*, and W.E. MAY, “Historical notes on the deviation of the compass”, *op. cit.*, p. 220-222.

72. Harry D. HARRADON, “Some early contributions to the history of terrestrial magnetism – VII”, *Terrestrial Magnetism and Atmospheric Electricity*, vol. 49, n° 3, 1943, p. 185-186. This excludes Needham’s evidence of Chinese records of the problems of local magnetic anomalies – not the same as deviation – as early as Fei Xin (費信) (1436).

73. John Churchman (1753-1805) was an American land surveyor who worked for the districts of Delaware and Chester in Philadelphia.

74. David GUBBINS and Emilio HERRERO-BERVERA, *Encyclopedia of Geomagnetism and Paleomagnetism*, Dordrecht, Springer Verlag, 2007, p. 358; Siméon-Denis POISSON, “Sur les déviations de la boussole, produites par le fer des vaisseaux”, *Mémoires de l’Académie des Sciences de l’Institut de France*, vol. 16., 1838, p. 547-579 ; Ron DOERFLER, “Archibald Smith’s derivation of the basic equations of magnetic deviation” at <http://myreckonings.com/wordpress/wp-content/uploads/MagneticDeviation/MagneticDeviationEquations.pdf> accessed on 28.4.2014; Archibald SMITH, “On the mathematical formulae employed in the computation, reduction, and discussion of the deviations of the compass, with some practical deductions therefrom as to the mode of construction of iron-built vessels”, *Transactions of the Institution of Naval Architects*, 1862, p. 65-73.

75. The full picture is more complex, see <http://geomag.nrcan.gc.ca/mag fld/comp-eng.php> accessed on 23.7.2014.

0. At the north and south magnetic poles the ratio is reversed.⁷⁶ Simply put, the greater the vertical component, the weaker the horizontal component, although we should note that the actual intensity of the Earth's magnetic field even at its greatest is small. A normal fridge magnet has an intensity of about 100 Gauss (10,000,000 nT) (nanoTesla). The Earth's magnetic field varies between 0.25 to 0.65 Gauss (25,000 and 65,000 nT). An important additional point to bear in mind in the context of Chinese directional pointers is that the intensity of the Earth's magnetic field has often been at its weakest over the South China Sea (as well as Southern Africa) being at those times under 30,000 nT.⁷⁷

If we note that this period of magnetic field weakness was at its greatest during the Ming Dynasty – a highpoint in Chinese long distance voyaging – we can also note that during the same period dip (sometimes called “inclination”) – or the tendency of the compass needle to point downwards responding to the vertical component of the Earth's magnetic field – was between 30° and 40° north-down along China's south coast, with changes of greater than ±10° at the extremes of the Chinese trading area.⁷⁸ It follows that compass needles will have been balanced to ensure they sat level for the inclination value and intensity of where they were made. Movement north to Japan or south to the nanyang with their different values and intensities of dip will have made the needle vulnerable to capsize in rough weather.⁷⁹

Chinese observers noted variation possibly as early as the 8th century CE and certainly by the 11th century.⁸⁰ However, despite awareness that varia-

76. Nathaniel BOWDITCH, *The American Practical Navigator: an epitome of navigation*, Millennium ed., Washington, National Imagery and Mapping Agency, 2013, chapter 6, p. 81.

77. <http://wdc.kugi.kyoto-u.ac.jp/igrf/animel/1600.gif> accessed on 17.4.2014.

78. Ronald T. MERRILL and Michael W. McELHINNY, *The Earth's Magnetic Field: Its History, Origin and Planetary Perspective*, New York, Academic Press, 1983, chapter 4.

79. Today compasses come in relation to what are known as “balance zones”. There are up to seven depending on manufacturer and compass cost. When using northern hemisphere balanced hand-bearing and steering compasses in the southern Tasman Sea the author found the former – a “puck” compass – jammed and was useless and the latter occasionally inverted (the compass card turned upside down) in lively seas and because of imbalance was hard to read if the helmsman was sat down. See for example <https://www.ritchienavigation.com/resource-center/instructions/zone-balancing/> (accessed 21.4.2018) for an image of balance zones.

80. The normally cited *locus classicus* in China for variation/declination is Kuo SHEN (沈括) (c.1088CE), see Nathan SIVIN, *Science in ancient China: researches and reflections*, Ashgate, Variorum Press, 1995, p. 21-33.

tion changed in geographical space and through time, there was neither a systematic understanding nor any record of values outside China that would have allowed any practices of median compensation to have arisen. There is no evidence that dip (inclination) was understood any more than deviation seems to have been.⁸¹ I shall come back to these two very important absences below.

The compass needle

To work usefully on a ship a magnetic compass needle must have a number of properties. Without them the needle will not reliably point north/south. It will be hard or perhaps impossible to steer by or take bearings of distant objects from. It will work only over a certain range of latitude.

First, the magnetism of the compass needle must be strong enough to respond to the weak geomagnetic force. That is, its magnetic moment (measured in $\text{A}\cdot\text{m}^2$) (amperes•metres squared) must be great enough to respond to the Earth's relatively weak magnetic field.

— 174 The primary source for magnetic strength is a permanently magnetized needle. Whilst it is thought to be the case that some Chinese compass needles had more durable magnetism thanks to thermoremanent magnetization and an early use of steel rather than iron, the magnetization was weak. Other needles were magnetized, like European ones, by use of a lodestone.⁸² No needles in any part of the world were both strongly and durably magnetized until the work of Gowin Knight in Britain in the mid-18th century. Knight did not fully understand why what he achieved worked – that came later – but he made two major breakthroughs.⁸³ He was able powerfully and durably to magnetize steel, though exactly how he magnetized his magnetizing apparatus is still uncertain. Second, by experiment he showed that the commonly used soft iron wire needles and steel bar needles were weak, impermanent and, in the case of shapes that were

81. R.T. MERRILL and M.W. McELHINNY, *The Earth's Magnetic Field*, *op. cit.*, p. 6.

82. Joseph NEEDHAM, Ling WANG and Kenneth G. ROBINSON, *Science and Civilisation in China: Vol. 4, Physics and Physical Technology*, Part 1, *Physics*. Cambridge, Cambridge University Press, 1962, p. 252-253. A lodestone is a more or less shaped piece of naturally occurring magnetite (Fe_3O_4 or more strictly $\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$).

83. Richard B. PROSSER, "Knight, Gowin", *Dictionary of National Biography, 1885-1900*, vol. 31, at http://en.wikisource.org/wiki/Dictionary_of_National_Biography,_1885-1900/Volume_31 accessed on 22.4.2014.

not simple bars or pins and when pierced for or fitted with a pivot cap, multipolar.

For example the Royal Navy's double-trapezium type had six poles, the common compass maker's, diamond-shaped bent and brazed wire type had at least four. Both were directionally unstable. Knight's researches recommended a plain bar needle NOT pierced for a pivot cap, but attached to a thin, circular card surrounded with a brass rim in the centre of which the pivot cap was fixed.⁸⁴ It should be noted that the needle most commonly associated with the Qing Dynasty, dry pivot compass used on Chinese vessels has at least six poles. The magnetized, floating 'fish' described in Zeng Gongliang (曾公亮), Ding Du (丁度) and Yang Weide (楊惟德), *Wujing Zongyao* (武經總要) in 1044 (of which an imagined reconstruction is illustrated in Needham and Ronan) would have had something like eight poles.⁸⁵

In general even after Gowin Knight's work it was thought (rightly) that the longer a needle the stronger its magnetism would be. Needles up to 0.38m long were favoured. This was because such needles were thought to be more stable and to oscillate less (have a shorter beat as this is termed). In a scholar's study or on a terrestrial surveyor's plane table this is true. In a seaway aboard ship it is the converse. Long needles are chronically unstable as, in general, are single needles. Further research by Archibald Smith and FJ Evans in the 1850s showed that in fact multiple, parallel short bar needles, their lengths and the distances between them related to carefully calibrated angles between their tips, were the most stable configuration.⁸⁶ Finally, each of the needles should be made of fine, laminated, tempered, hard steel.⁸⁷ The apex of dry pivot design, Kelvin's 1875 Dry Card Compass, had eight such parallel, precisely graduated needles, of carefully calibrated lengths to ensure the correct angle between their tips, slung by silk threads below and either side of the pivot to reduce beat.

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84. Gowin KNIGHT, "A description of the Mariner's Compass contrived by Gowin Knight, MB, FRS", *Philosophical Transactions of the Royal Society*, n° 46, 1749, p. 505-512.

85. For the imagined reconstruction see J. NEEDHAM and C.A. RONAN, *The Shorter Science and Civilisation in China*, op. cit., p. 12, 46.

86. <http://myreckonings.com/wordpress/wpcontent/uploads/MagneticDeviation/MagneticDeviationandDyogogram.pdf>, p. 8 accessed on 22 april 2014

87. Timothy A. LYONS, *A Treatise on Electromagnetic Phenomena, and on the Compass and Its Deviations Aboard Ship: Mathematical, Theoretical, and Practical*, vol. II, New York, J. Wiley & Sons, 1901, chapter XIV.

Mechanical efficiency

Mechanical efficiency in a compass – and usually absent in any early magnetic pointer – comes down to three aspects.

First, the compass must be so designed as to minimize the effects of the ship's motion on its accuracy. This was tackled in four ways. We have noted that by the beginning of the 16th century in the West the gimbal mounting was in use. This simple device, if it is well-made and has freely moving pivots, keeps the compass level in all conditions but the most severe. In such conditions traditional ships of whatever nationality were surviving, not being steered, so we can consider gimbals to be generally useful in all less fraught conditions. However, although the gimbal was helpful, it was not absolutely vital for our conjectured water-bowl, floating magnetic pointer since a floating needle in calm to moderate conditions adjusts to a ship's movement.⁸⁸ Similarly, the earliest known late Ming or early Qing dynasty dry pivot needle, on its tall pivot, had plenty of space below and above it to compensate for normal motion.

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With keeping the compass or needle level dealt with, the emphasis shifts to the quality of the pivot. There are two elements to this. One is simply the durability and lack of friction in the pivot itself. This in time led to the use of either naturally lubricated bearings in materials like ivory or lignum vitae, or to jeweled or very hard metal bearings both for the axle and the 'cup' which rode on the axle's tip. In general a support from beneath the card presented an easier task than a suspended pivot, which is why most compasses were made that way. Again, in principle a floating needle would seem to solve the problem of a durable and friction free pivot.

That the pivot had more problems than minimum friction and durability brings us to the third design feature that developed to improve the needle's maintenance of a steady direction. This was the realization that the needle was more stable if the point of pivot was above the needle's center of gravity. That was achieved by designing the compass needle layout with a 'cup' at the center of rotation that had its apex above the needle's plane. Here a floating needle, unless somehow suspended beneath its flotation device, is not advantaged.

88. For an image of a conjectured Ming Dynasty floating needle compass see J. NEEDHAM and C.A. RONAN, *The Shorter Science and Civilisation in China*, *op. cit.*, p. 252.

Finally, and much the most difficult problem of all, was how to damp the oscillations of the compass needle (its “beat”) as it responded to the movements of the ship and to changes of course. These could on occasions be so severe, even in the middle of the 19th century, as to have the compass card swinging 90° either side of the centerline and even on occasions spinning.⁸⁹

The solution of using a liquid to surround an otherwise “dry” pivoted needle – very different to the Ming Dynasty floating needle – was slow to be realized.⁹⁰ The first liquid compass was designed by a British instrument maker, Francis Crow, in 1813. It never took off until American E.S. Ritchie took up its basic design in 1862. In the meantime enormous ingenuity was spent on trying to improve the dry pivot compass using large, extremely light cards, etc., but in a lively seaway none ever proved reliable.⁹¹

More important if the ship was to be steered by compass were two other mechanical changes. All were designed to ensure that the helmsman could read the compass accurately at a glance. This was achieved first by combining compass needle and the compass card or rose so that they rotated together. This was better than having a fixed card or set of compass points on the compass container or body with a freely rotating needle within or above it. That is because with a fixed compass body or rose, the course point has to be aligned with the ship’s centerline at every change of course. However, with a needle-cum-compass rose the compass is more easily used if a lubber line or reference point aligned with the ships fore-and-aft line is fixed on the compass body. The ship and compass body may then freely twist and turn under the compass card and attached magnetized pointer, which always points steadily north/south with the lubber line pointer indicating the direction of the ship’s head. This innovation had become

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89. W. WALKER, *The Magnetism of Ships and the Mariner’s Compass*, *op. cit.*, p. 168.

90. Think of a dry pivot compass in which the ‘air’ in which the compass card moves is a more viscous liquid medium. Filling liquids have to be degassed and can be purified kerosene (paraffin), isopropyl alcohol, or a distilled water/alcohol or water/glycerine mix.

91. Alan GURNEY, *Compass: a Story of Exploration and Innovation*, New York, WW Norton, 2004, is an excellent general guide. Anthony E. FANNING, *Steady as she goes: a history of the Compass Department of the Admiralty*, London, HMSO, 1986, is fascinating on technical detail, especially the dry pivot Admiralty Standard Compass that was the Royal Navy’s standard issue followed from 1889 to the early years of the 20th century. The Admiralty Standard Compass and its close relative enjoyed some 75 years of not entirely merited dominance. See also David LINDLEY, *Degrees Kelvin: A Tale of Genius, Invention and Tragedy*, Washington DC, Joseph Henry Press, 2004, p. 252-259.

standard in most western compasses by the end of the 17th century, though appears never to have been customary with Chinese magnetic pointers, whether water bowl or dry pivot, emphasizing again that whatever the Chinese instrument was used for, it was not as a steering aid.

Design principles for a navigationally useful compass

The result of all these changes was a set of fundamental design requirements that any successful magnetic pointer had to satisfy if it was to become a marine compass and, therefore, a useful navigational aid. Only after sufficient progress towards satisfying the requirements had been made – roughly the point that had been reached in the western world by the early-to-mid-16th century – was a useful, though not always entirely reliable instrument available. The needle must have reasonably durable permanent magnetism with a strong magnetic moment, a low enough friction pivot and basic compensation for dip/inclination. The needle or its card must not have too great a beat. And the instrument as a whole must be so designed as sufficiently to reduce the effects of ship's movement and reliably and steadily show the direction of the ship's head.

It is important to reiterate that the object here has been to make clear what is needed in a magnetic pointer for it to become a reasonably accurate and reliable navigational tool *at sea*. In short a mariner's compass that orientated, gave direction, could be used to steer by and to take bearings with. I have described how long that took looking at the matter of the compass as a general technological challenge and what the problems were that had to be overcome. By extension, therefore, we have indicated how far from sufficiently meeting the required design parameters known traditional Chinese magnetic pointers were. This is not an indictment. It is a pointer to the different navigational techniques practiced in European and Asian sea areas we considered above. In the former necessity and, more arguably, a different cultural context “pushed” the slow developmental progress. In the latter there was no significant navigational “push”, so the ingenuity of China's mariners was not called upon to provide the practical fixes of which, we can be sure, they were fully capable had the need arose. Whether, had a design “push” from navigational need begun the necessary development, something similar would have occurred in China to

the theorization of what underlay the practical problem that we see in the western world from Gilbert onwards, is accordingly moot.

A tentative conclusion

The puzzle with which I began was what I styled a variant of the Needham question, provoked by a widespread way of writing about how Chinese seafarers used compass based navigation, backed by reference to surviving rutters and charts, with the implication that the latter were both a product of and, for sailing in accordance with their instructions, dependent on the existence and use of a magnetic pointer understood as a marine compass.⁹² The variant of the question was why, given the early invention of a magnetic pointer and of taking it to sea, in China no comparable technical or theoretical developments to those we find in the Western world took place. In China, accordingly, we find no virtuous feedback circle whereby better theoretical understanding helped technical development and a rude magnetic pointer turned into a mariner's compass.

The evidence, admittedly largely inferential and circumstantial, suggests that the nature of traditional Chinese navigation was not – or not obviously – compass based in the sense that Needham misleadingly used that term in his magnum opus; that is, in the sense that any modern navigator would use it.⁹³ The simple reason here is that in use the water-bowl magnetic pointer could not have acted as a useable and reliable sea-going navigational aid for course keeping or for determining the bearings (or azimuths) of shore marks or heavenly bodies. Had there been any attempt so to use it, then the technical abilities of Chinese mariners would have addressed the shortcomings of so extremely primitive an instrument and devised incremental 'fixes' much as did their *confrères* in the West, though not necessarily the same ones. But whatever the fixes were, they would

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92. In a most helpful comment, reflecting on the similarity between early Portuguese rutters and the few remaining early Chinese examples, Pierre-Yves Manguin asks whether the latter may reveal the use by Chinese pilots of compass technology borrowed from Portuguese examples, of which they would have become aware as western voyagers penetrated Asian seas in the 16th century, when developments to western compasses were still comparatively young. As he notes, a careful comparative evaluation of European and Chinese rutters might help decide on this matter, but this is beyond the scope of this paper.

93. J. NEEDHAM, L. WANG, K.G. ROBINSON, *Science and Civilisation in China. Physics, op. cit.*, p. 284.

have been ones that solved the same problems. That is, a fix that ensured steady and reliable magnetization of the pointer. Compensation for dip/inclination. Effective damping to reduce or eliminate beat. And an overall design that eliminated the effects of ship's movement and, by reliably and steadily showing the direction of the ship's head, enabled the helmsman to steer by compass and the navigator to take reliable bearings.

Equally, had the pointer been in regular use as a steering and locational aid over the range of Chinese voyaging, there would be traces in Chinese literature of an awareness of the more theoretical aspects of the problems and how they affected the value of the magnetic pointer for other than use as an emergency tool for reorientation. Whilst it is clear that there was a long-standing awareness of the actuality of variation, of its difference by place within China and of its change over time (secular change), this was an awareness of the fact only.⁹⁴ There would appear to have been no impulse, of the kind that the exigencies of long-distance, compass based navigation seems to have induced or at least encouraged in the western world, to come up with any of the sort of theorization and mapping that we find, for example, in the work of William Gilbert and his terella, and in his path-breaking *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* of 1600, or Edmund Halley's famous declination map of the Atlantic and Pacific, using his own data and the data of others, and his invention of isogonic, or Halleyan lines, of 1701.⁹⁵ And despite Needham's somewhat dubious claims about local magnetic anomalies, there is no evidence of any awareness of dip and how that changed, or of deviation and how it changed both by vessel and, in any given vessel, by course steered.

In sum, what Chinese navigational sources seem to be telling us is that their traditional seafarers steered on well-established courses, measured in terms of standard units of time, usually the *geng* (更), though not always,⁹⁶

94. J. NEEDHAM and C.A. RONAN, *The Shorter Science and Civilisation in China*, *op. cit.*, p. 37-46.

95. Edmund HALLEY, *A New and Correct Chart of the Whole World showing the Variations of the Compass as they were found in the year 1700*, London, 1702, Royal Museums Greenwich, National Maritime Museum, G201:1/1A, G201:1/1B, see also Charles H. COTTER, "The Royal Society and the Deviation of the Compass", *Notes and Records of the Royal Society of London*, vol. 31, n° 2, 1977, p. 297-309; Louis A. BAUER, "Halley's earliest equal variation chart", *Terrestrial Magnetism*, vol. 1.1, 1896, p. 28-31; Louis A. BAUER, "Magnetic results of Halley's expedition, 1698-1700", *Terrestrial Magnetism and Atmospheric Electricity*, vol. 18.3, 1913, p. 113-126.

96. For example, in the Taiwan Straits where, uniquely on the coasts of China, there are regular semi-diurnal tides (*cháo* 潮) with highs and lows separated by 6h 12.5 minutes, the period of which

related to the speed of advance of their vessel in ways that are by no means certain.⁹⁷ Directions were related to the way in which the visual horizon was divided up to orientate the observer: something of great antiquity that far predated any direction pointing device and was entirely independent of it. We also infer as a consequence that the seafarers kept direction in terms of this sectorized horizon using natural indicators – wind, run of sea, positions of heavenly bodies – that we know to have been used, and used with enormous success, by Arab, Indonesian, Polynesian and other navigators.

These seafarers had on board, for use *in extremis* (and, *sotto voce*, perhaps from time to time to impress embarked landlubbers with wizardry), an unreliable, water-bowl based, magnetic pointer for use to help relocate south should they get completely disorientated. So unreliable was it, indeed, that there would appear to have been widespread treatment of it as a ritual, or quasi-ritual object the reliability of which depended on the correct pre-voyage invocations and, on any occasion of use, by the proper performance of established rituals, presided over by the guardian of the shipboard shrine and the pointer. Nothing in Chinese mariners' extensive voyaging routes and their sailing seasons seems to have required them to move beyond this. Furthermore, the cultural and intellectual context within which their voyages took place was not one in which either the practical or the theoretical problems of seafarers were of significant interest, or in which the turn of mind that resulted in the scientific revolution in the western world had any purchase. So, in the terms used in this discussion, despite extensive, far ranging and well-conducted voyaging, the Chinese magnetic pointer never became a compass.

That is not a cause for disparagement, but for wonder at so simple and low cost, yet so reliable and enduring a system of navigation.

Chinese seafarers used as their time measure. I owe my knowledge of this to Paola Calanca.

97. A note of hesitation is also appropriate with respect to claims that the simple chip log was in wide use, based on exactly the same kind of reasoning. That is, there are no obvious signs of development of the sort one would have expected skilled mariners to devise. No mention of any standard unit of linear sea distance. No push to devise more accurate – or indeed any sort of accurate – shipboard timepieces. No development of anything like the well-known, German made tobacco boxes with speed/time/distance cribs for a chip log of the kind associated with Pieter Holm's early 18th century Amsterdam navigation school (see <http://staff.science.uu.nl> accessed on 12th June 2015). There appears to be no development, either, of the essential tools like traverse boards or a written logbook for recording the gathered data, or at least none that have been publicly discussed.

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