

# 20 • Navigation Techniques and Practice in the Renaissance

ERIC H. ASH

The Spanish cosmographer Martín Cortés, in introducing the art of navigation to the readers of his 1551 instructional manual on the subject, called it one of the “difficultest things” a man could undertake. Navigation, which Cortés defined simply as “to journey or viage by water, fr[om] one place to another,” differed crucially from land travel in that, while the latter was “known and [de]termined by markes, signes, and limites,” travel by sea was “uncerten and unknowen” for want of stable reference points on the open seas. “Therefore these viages beyng so difficile,” he wrote, “it shal be hard to make the same be understode by wordes or wrytyng.” In order to get around the sticky problem of explaining such a challenging art in prose alone, Cortés turned to nautical cartography as a means to illustrate his lessons: “The best explication or inuention that the wyttes of men haue founde for the manifestyng of this, is to geue the same paynted in a Carde.”<sup>1</sup>

The many voyages of exploration undertaken during the early modern period, and the long-distance trade networks that eventually grew out of them, necessitated and fostered a number of qualitative changes to the ancient art of navigation. Whereas medieval pilots had relied primarily on their intensive personal familiarity with the routes they sailed in order to find their way, the early modern explorer had no similar empirical frame of reference to guide him in strange waters, and the transoceanic pilot had no landmarks whatsoever to assist him on the open sea.<sup>2</sup> To help him determine his location in the middle of the ocean, the pilot came to rely on the fixed stars as his principal reference points, taking a variety of simplified astronomers’ instruments to sea with him for that purpose.<sup>3</sup> Yet figuring out his ship’s position was only one of the challenges the early modern pilot faced; he also had to decide where to steer his ship in order to reach his intended landfall. For this he turned to various early modern adaptations of the medieval portolan chart, a device that allowed Mediterranean pilots (in theory) to calculate the compass heading and distance between any two places depicted on the chart. As European pilots guided their ships to all corners of the globe, marine cartography adapted to meet their changing needs.

## THE MEDIEVAL CRAFT OF PILOTAGE

One of the greatest difficulties in traveling by sea, as Cortés pointed out, has always been navigating without recourse to fixed landmarks. In the absence of roads, paths, inns, signs, and other navigational cues, finding one’s position and determining one’s intended course could be an intractable problem. The simplest and most obvious solution for shorter voyages, of course, was to stay within sight

---

Abbreviations used in this chapter include: *HPC* for Armando Cortesão, *History of Portuguese Cartography*, 2 vols. (Coimbra: Junta de Investigações do Ultramar-Lisboa, 1969–71).

1. Martín Cortés, *Breue compendio de la sphaera y de la arte de nauigar con nuevos instrumentos y reglas . . .* (Seville: Anton Aluarez, 1551), and idem, *The Arte of Nauigation . . .*, trans. Richard Eden (London: R. Jugge, 1561), fol. lvi. For a facsimile reprint, see Martín Cortés, *Arte of Navigation (1561)*, intro. David Watkin Waters (Delmar, N.Y.: Scholars’ Facsimiles and Reprints, 1992).

2. Some historians, especially Waters, have divided early modern navigational practitioners into two types, to whom they usually refer as pilots and navigators. Whereas pilots, according to this distinction, based their art solely upon local, empirically based knowledge, navigators are understood to have mastered the mathematical, astronomical, and theoretically based knowledge that allowed them to plot courses and sail in waters where they lacked the sort of personal experience connoted by pilotage. See David Watkin Waters, *The Art of Navigation in England in Elizabethan and Early Stuart Times* (London: Hollis and Carter, 1958), 3–5. The differentiation does have some basis in early modern sources; Richard Eden, for example, in the preface to his 1561 translation of Cortés’s *Arte of Nauigation*, drew a sharp distinction between those who could navigate anywhere and those who were bound to sail only in the shallow waters, rivers, and bays long familiar to them, though he did not differentiate his terminology (fol. [C.iv verso]–CC.i). Still, the strict separation is often problematic from a historical standpoint; Pablo E. Pérez-Mallaína and Alison Sandman have both done much to show that the pilot-navigator dichotomy may be more usefully considered as a spectrum of navigational knowledge and experience (see the citations that follow). For this chapter, I have chosen to use the term “pilot” to refer to all navigational practitioners, regardless of which techniques they used.

3. Celestial navigation, however, provided only a limited solution to the problem of determining one’s position at sea; while the sun and stars could be used to fix one’s latitude, it was impossible to calculate accurately one’s longitude aboard a ship until the middle of the eighteenth century. All position calculations were therefore based to some extent on estimations of the distance already covered by the ship along a particular heading, as is explained later.

of the shoreline and simply follow the coast from one port to another; yet this strategy brought with it a host of disadvantages and dangers. For longer journeys (from Venice to Alexandria, for example, or from Norway to Iceland), a coastal route was often impracticable or impossible, while rough weather and shallow waters could also make hugging the coast a most hazardous way to travel, causing ships to run aground on rocks, shoals, and other obstructions that often remained unseen until too late. The quicker and safer strategy, therefore, was to take one's ship farther out to sea, where courses could be more direct, underwater hazards were less prevalent, and there was far more room to maneuver.<sup>4</sup>

Away from shore, however, the pilot was forced to rely on means other than fixed landmarks for finding, keeping, and confirming his intended course. No matter the route selected, the medieval art of navigation had always been firmly based on a pilot's personal experience. The good pilot was a highly experienced one who had spent several years sailing over all of his habitual routes and memorizing how to get from one particular port to another before ever being allowed to take the helm of a ship himself.<sup>5</sup> In addition to a thorough knowledge of local tides, currents, winds, and hazards, the two key pieces of information every pilot needed in order to keep his course were direction and distance: he had to know along which heading to steer his ship and roughly how long he must follow that heading to reach his destination. This method of heading and distance navigation was known as dead reckoning, and although it was vulnerable to any number of misleading inaccuracies, it also represented the medieval pilot's safest and most efficient means of guiding his ship.<sup>6</sup>

Once at sea, the pilot was able to monitor the heading along which his ship sailed by reference to occasional land sightings (rarely was the Mediterranean pilot, in particular, out of sight of land for more than a few days), by making sure that he kept a straight wake behind him, or by harking to astronomical cues: the direction of the Pole Star or the bearing of the sun at noon, when it reached its highest (and southernmost) point. He estimated the distance his ship had covered along a given heading either by feel, acquired empirically through long experience at sea, or else by measuring his ship's progress with respect to some floating bit of foam or flotsam and then extrapolating from it. One method that may have been used as early as the fifteenth century involved dropping wood chips into the water and timing (with a small sandglass or by reciting a simple rhyming phrase) how long it took them to float between two points on the side of the ship's hull, a known distance apart. Then, perhaps with the help of a mathematical conversion table, even a seminumerate pilot could calculate his ship's speed along the course he steered and estimate the time of his expected landfall.<sup>7</sup> Later pilots used the log and line to help them gauge their ships' speed;

this instrument consisted of a weighted log attached to a long rope, often knotted at regular intervals, and wound on a hand reel. One sailor tossed the log overboard, while another played out rope for a fixed time interval, usually half a minute, measured using a sandglass. The length of rope played out was then measured as the log was reeled in. Knowing the length of rope and the time elapsed, a numerate pilot could then calculate his ship's speed by working a simple ratio.<sup>8</sup> However, the first description of the log and line was written in England in 1574, and it may not have been available to pilots of an earlier period.<sup>9</sup>

Throughout the Middle Ages, the Mediterranean pilot's knowledge—consisting of the distances and headings between various ports as well as important information regarding tides, currents, prevailing winds, dangerous shoals, and key landmarks—was traditionally handed down from master pilots to their apprentices. Every aspiring pilot had to sail his routes repeatedly, under the

4. J. B. Hewson, *A History of the Practice of Navigation*, 2d rev. ed. (Glasgow: Brown, Son and Ferguson, 1983), 1–3; Waters, *Art of Navigation*, 3–7; E. G. R. Taylor, *The Haven-Finding Art: A History of Navigation from Odysseus to Captain Cook*, new aug. ed. (New York: American Elsevier, 1971), 4; and Frederic C. Lane, "The Economic Meaning of the Invention of the Compass," *American Historical Review* 68 (1963): 605–17, esp. 607. Historians of navigation disagree regarding the extent to which coastal sailing was actually practiced before the introduction of the magnetic compass and nautical chart. Hewson and Waters both imply that it was once a standard method of navigation, while Taylor and Lane argue that mariners have always been wary of the dangers of sailing too close to land.

5. Waters, *Art of Navigation*, 3–7 and 495–96. The modern art of pilotage, though limited to the inner waterways of particular rivers and harbors, is still learned in very much the same way. For an excellent and engaging modern account of pilotage and the ways in which it is taught and learned, see Mark Twain, *Life on the Mississippi* (Boston: James Osgood and Company, 1883).

6. David Watkin Waters, "Reflections upon Some Navigational and Hydrographic Problems of the XVth Century Related to the Voyage of Bartholomew Dias, 1487–88," *Revista da Universidade de Coimbra* 34 (1987): 275–347; idem, "Early Time and Distance Measurement at Sea," *Journal of the Institute of Navigation* 8 (1955): 153–73; idem, *Art of Navigation*, 36–37; E. G. R. Taylor, "The Sailor in the Middle Ages," *Journal of the Institute of Navigation* 1 (1948): 191–96; idem, "Five Centuries of Dead Reckoning," *Journal of the Institute of Navigation* 3 (1950): 280–85; idem, *Haven-Finding Art*, 122; J. E. D. Williams, *From Sails to Satellites: The Origin and Development of Navigational Science* (Oxford: Oxford University Press, 1992), 21–40; and Hewson, *Practice of Navigation*, 178–225.

7. James E. Kelley, "Perspectives on the Origins and Uses of the Portolan Charts," *Cartographica* 32, no. 3 (1995): 1–16, esp. 12 n. 11. Though this method was popular with Dutch mariners in the seventeenth and eighteenth centuries, there is no evidence that it was actually used before that time; see J. A. Bennett, *The Divided Circle: A History of Instruments for Astronomy, Navigation and Surveying* (Oxford: Phaidon, 1987), 31, and W. E. May, *A History of Marine Navigation* (Henley-on-Thames, Eng.: G. T. Foulis, 1973), 109.

8. Bennett, *Divided Circle*, 31.

9. The description appears in William Bourne, *A Regiment for the Sea . . .* (London: Thomas Hackett, 1574), 42–43.

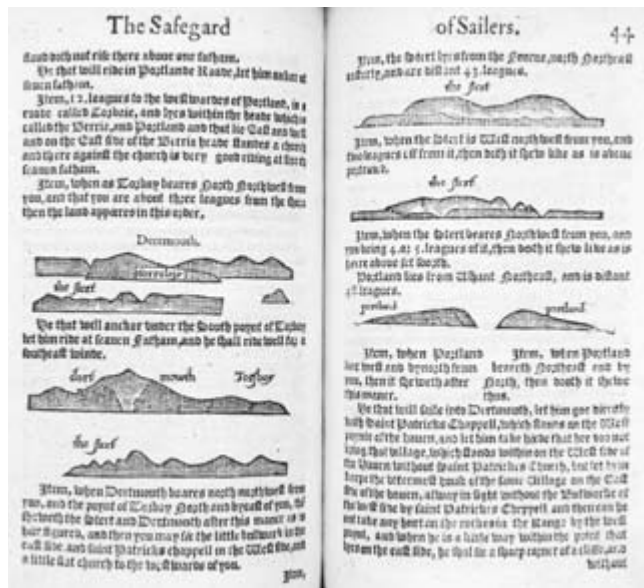


FIG. 20.1. A TYPICAL PAGE FROM THE RUTTER *THE SAFEGARDE OF SAYLERS*, 1590. Although this was a published work, most rutters circulated in manuscript form. This work contained little more than a collection of compass headings, estimated distances, and rough sketches of coastal features and landmarks by which the pilot was supposed to guide his ship.

Size of the original page: ca. 19 × 12.1 cm. Cornelis Anthonisz., *The Safegarde of Sayers, or Great Rutter . . .*, trans. Robert Norman (London: Edward Allde, 1590). Photograph courtesy of the BL.

supervision of a more experienced mentor, before he could be entrusted with the safety of ship, crew, and cargo on his own.<sup>10</sup> Some literate pilots took the step of recording and compiling their store of knowledge in written form, for use both as an instructional aid for apprentices and as a helpful reminder for themselves when sailing less familiar routes. Such a written document was known in Italian as a *portolano*, and in French as a *routier*; the English corrupted the latter into the word “rutter” (fig. 20.1).<sup>11</sup> Collections of such navigational data may well have been in use from ancient times, but they became popular in the Mediterranean during the late medieval period. Such works proliferated, circulating mainly among Mediterranean pilots first in manuscript and later in printed form, from the fourteenth century onward.<sup>12</sup>

The earliest surviving rutter, known as “Lo compasso da navigare,” was written in the Italian vernacular and dated 1296, though it probably represents a revision of an even earlier original, now lost. This small manuscript lists the distances and bearings between ports throughout the Mediterranean and Black seas, as well as data regarding water depth, anchorages, and landmarks for recognizing the approaches to various harbors.<sup>13</sup> Though the majority of the work is dedicated to routes that hug

the coastline, it also contains information describing over two hundred long-distance, pelagic routes that would have taken pilots well out of sight of land. Surprisingly, Lanman has demonstrated that the longer, open-sea courses were by far the most accurate in their description of both bearing and distance measurements. Lanman argues, therefore, that early rutters were most useful for precisely the sort of oceanic navigation that pilots already favored as being safer and more efficient.<sup>14</sup>

Besides keeping track of his heading and the distance sailed, the pilot also had to do his best to correct for navigational “noise.” Maintaining a constant heading by keeping a straight wake, or by relying on celestial reference points that might be obscured by clouds for days at a time, was already difficult enough; phenomena such as leeward drift, tidal currents, disagreeable winds, and storms could push even the most careful pilot several leagues off his intended course.<sup>15</sup> By the late Middle Ages, pilots on the Mediterranean had two instruments to help them keep their course or return to it if they had strayed. The first of these was the magnetic compass.<sup>16</sup> Although the invention of the compass has been claimed for the Chinese, the Arabs, and both Mediterranean and North Atlantic Europeans, its precise origins remain a mystery, and indepen-

10. Waters, *Art of Navigation*, 3–7.

11. David Watkin Waters, *The Rutters of the Sea: The Sailing Directions of Pierre Garcie. A Study of the First English and French Printed Sailing Directions* (New Haven: Yale University Press, 1967); idem, *Art of Navigation*, 11–14; Taylor, *Haven-Finding Art*, 89–148; and Hewson, *Practice of Navigation*, 16–21.

12. Rutters were less common (though not unknown) among North and Baltic Sea mariners during the same period, perhaps because those pilots did not rely entirely on dead reckoning navigational techniques. Instead, because the seas around northern Europe are fairly shallow, pilots in that region learned to navigate using their lead and line. By coating the bottom of a lead weight with tallow and throwing it overboard attached to a cable, the pilot was able to determine not only the water depth, but the condition of the seabed beneath his ship. An experienced pilot could then interpret this information to determine his position at sea relative to his destination and guide his ship accordingly; in essence, he used the condition and depth of the seafloor as a sort of submerged, surrogate landmark to guide his way. See Taylor, *Haven-Finding Art*, 131, and Lane, “Invention of the Compass,” 611.

13. E. G. R. Taylor, “The Oldest Mediterranean Pilot,” *Journal of the Institute of Navigation* 4 (1951): 81–85; idem, *Haven-Finding Art*, 102–9 and 131–36; Waters, *Art of Navigation*, 11–14; and Hewson, *Practice of Navigation*, 16–21. Bacchisio R. Motzo, “Il compasso da navigare, opera italiana della metà del secolo XIII,” *Annali della Facoltà di Lettere e Filosofia della Università di Cagliari* 8 (1947): 1–137.

14. Jonathan T. Lanman, *On the Origin of Portolan Charts* (Chicago: Newberry Library, 1987), 19–21.

15. Tidal currents were a considerable problem for mariners of the North Atlantic but played a relatively minor role within the confines of the Mediterranean Sea; see Waters, “Reflections,” 301–6. Likewise, severe storms were not a common threat to Mediterranean pilots in the summer sailing months; see Lane, “Invention of the Compass,” 606–8.

16. On the early history of the magnetic compass in Europe, see Barbara M. Kreutz, “Mediterranean Contributions to the Medieval





FIG. 20.2. PART OF A MANUSCRIPT *TOLETA DE MARTELOIO*.

Size of the original: ca. 41.8 × 14.5 cm. Photograph courtesy of the BL (Egerton MS 73, fol. 47v).

dent development among diverse maritime populations is not unlikely. In the European context, the earliest reference to sailors' using a magnetic needle as a means of locating north was written by an English Augustinian monk, Alexander Neckam, in the late twelfth century.<sup>17</sup>

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. Sometime during the fourteenth century, the needle was attached to a circular card, called a compass fly, depicting the various wind directions; the fly and needle assembly was then placed on a pivot and housed in a gimballed box to reduce the effects of wind and the ship's movement.<sup>18</sup> By the late sixteenth century, the box itself had been fixed to the helm of the ship and marked with a line (called a lubber's line) showing the direction of the ship's prow, allowing the pilot to know simultaneously where north was located and his ship's heading with respect to it.<sup>19</sup> The compass obviously gave the pilot an enormous advantage in maintaining his course, for he was no longer dependent on clear skies or infrequent land sightings to take his bearings. The magnetic compass allowed him to guide his ship along any heading, wind and weather permitting, with much greater confidence.<sup>20</sup>

Of course, wind and weather did not always permit such an easy, straightforward voyage; often a pilot was forced many leagues off his intended course in order to take advantage of such winds as were available. By the end of the thirteenth century, the pilot probably carried with him a *toleta de marteloio* in order to return to his chosen route. The *toleta* was really an early set of trigonometric tables and geometrical diagrams designed to tell the pilot how far he had been diverted from his original course and how far along a given heading he would have to sail to recover it (fig. 20.2). Provided he had been able to keep track of the heading and distance his ship had ac-

Mariner's Compass," *Technology and Culture* 14 (1973): 367–83; W. E. May, "The Birth of the Compass," *Journal of the Institute of Navigation* 2 (1949): 259–63; idem, *Marine Navigation*, 43–107; G. J. Marcus, "The Mariner's Compass: Its Influence upon Navigation in the Later Middle Ages," *History* 41 (1956): 16–24; Lane, "Invention of the Compass"; Taylor, *Haven-Finding Art*, 89–102; Hewson, *Practice of Navigation*, 45–51; and Waters, *Art of Navigation*, 21–35.

17. Taylor, *Haven-Finding Art*, 95–96; May, *Marine Navigation*, 45–53; idem, "Birth of the Compass," 259–61; and Kreutz, "Mediterranean Contributions," 368–69. Kreutz suggests in her article that the medieval European version of the compass may have been influenced by cultic uses of magnetism in ancient Samothrace (pp. 378–83).

18. May, *Marine Navigation*, 50–51, and Hewson, *Practice of Navigation*, 49–51.

19. Bennett, *Divided Circle*, 29.

20. Lane has argued that the very nature of Mediterranean shipping was radically altered by the introduction of the magnetic compass, so the often overcast winter months became newly navigable, whereas

tually sailed (not always possible if he had been driven off course by a storm), the pilot could refer to the tables to determine roughly where he was and how to get back to where he wanted to be.<sup>21</sup> The mathematics required to use such a table involved multiplication and division, however, and may well have been beyond the mathematical abilities of the majority of medieval pilots, a point to which I return later.

Finally, while the medieval rutter, the magnetic compass, and the *toleta de marteloio* had helped to make pelagic navigation considerably easier, giving Mediterranean pilots greater confidence in venturing out onto the open sea, by the late Middle Ages pilots had yet another new tool to assist them: the nautical chart. Although their precise origins remain obscure, the development of medieval nautical charts appears to have been so closely linked with the use of rutters that today they are usually referred to as “portolan charts,” from the Italian word for rutter, *portolano*.<sup>22</sup> Exactly how pilots used their charts is not entirely certain, though there can be little doubt that portolan charts did constitute part of a late medieval pilot’s standard equipment, at least within the bounds of the Mediterranean Sea. Contemporary references from as early as 1270 indicate that charts were already commonly found aboard ship, and by the end of the fourteenth century several Mediterranean maritime authorities had decreed that every ship must carry at least two charts on board.<sup>23</sup>

Portolan charts most likely served as a complement to the navigational instructions contained in Mediterranean rutters and may have been used in planning and tracking long-distance voyages during which the pilot was often not within sight of land. According to this theory, the chart’s visual depiction of the space between two relatively distant ports would have allowed the pilot to plot a pelagic course with greater accuracy and confidence than he could have done using only the estimated distances and headings contained in his rutter.<sup>24</sup> To plot an optimal dead reckoning course for any given route using a portolan chart, the pilot first had to locate his port of origin and his destination on the chart and draw a straight line between them. Then, with a pair of dividers, he could use the rhumb lines and distance scale contained within the chart itself to determine the appropriate compass heading he would have to maintain to sail between the two points and estimate how far along his selected heading he would have to travel.

The portolan chart, then, represented a considerable advance beyond the basic rutter; whereas the rutter contained only a more or less limited list of specific navigational data, the chart could be applied much more broadly. A good portolan chart amounted to nothing less than a highly versatile visual representation of the two key pieces of information most relevant for any given course: distance and bearing. It was equally valid for a great

many different courses, limited only by the number of ports depicted within it. With a pencil and a pair of dividers, a cartographically minded pilot could potentially use his chart to determine the heading and distance between *any* two points contained within the chart itself, not merely those listed in his rutter. He could also use it to plot a more direct or convenient oceanic course than his rutter recommended, for many rutters concentrated heavily on coastal routes. Portolan charts were thus a remarkably concise way to record and present vast amounts of navigational information as usefully as possible, the “best explication or inuention,” as Cortés wrote.<sup>25</sup>

Unfortunately, no one knows for certain whether portolan charts were actually used at sea in this way. Surviving charts generally lack the pencil marks and navigational scribbles one would expect to find on them if pilots had ever used them to set and maintain their ships’ courses across the open sea. It is possible that surviving charts were made for the consumption only of land-bound collectors rather than practicing pilots, and that actual working examples were all discarded as they wore out. Alternatively, pilots may have worked on traced copies in order to preserve their expensive charts and discarded the tracings when they were finished with them. In any case, contemporary references clearly indicate that some charts were taken to sea and intended for use as

---

prior generations of pilots had been unable to navigate without checking their bearings through celestial observation (“Invention of the Compass,” 606–10). In the North Sea, however, mariners apparently still preferred to navigate by the sun and stars whenever possible, even after the introduction of the compass; see Lane, “Invention of the Compass,” 611–13, and Marcus, “Mariner’s Compass,” 20.

21. E. G. R. Taylor, “Mathematics and the Navigator in the Thirteenth Century,” *Journal of the Institute of Navigation* 13 (1960): 1–12, esp. 10–12; idem, *Haven-Finding Art*, 117–21; Waters, “Reflections,” 320–27; Luís de Albuquerque, “Instruments for Measuring Altitude and the Art of Navigation,” in *HPC*, 2:359–442, esp. 434–39; and Tony Campbell, “Portolan Charts from the Late Thirteenth Century to 1500,” in *HC* 1:371–463, esp. 441–43.

The European use of the *toleta de marteloio* in dead reckoning bears a striking resemblance to the *tirfa* navigation technique of Islamic pilots in the Indian Ocean, used to locate the north-south position of their intended port. However, the *toleta* was almost certainly derived in the West from Arabic trigonometric and astronomical tables via Western European astronomers, although the exact means of transmission are not known. See Taylor, “Mathematics and the Navigator,” 10–12; Aḥmad ibn Mājid al-Sa’dī, *Arab Navigation in the Indian Ocean before the Coming of the Portuguese*, trans. Gerald R. Tibbetts (London: Royal Asiatic Society of Great Britain and Ireland, 1971), 299–312; David A. King, “On the Astronomical Tables of the Islamic Middle Ages,” in *Islamic Mathematical Astronomy*, by David A. King (Brookfield, Vt.: Variorum Reprints, 1986), item II; and E. S. Kennedy, “The History of Trigonometry,” in *Studies in the Islamic Exact Sciences*, by E. S. Kennedy et al. (Beirut: American University of Beirut, 1983), 3–29, esp. 3–5.

22. Campbell, “Portolan Charts,” 381–84, and also chapter 7 in this volume.

23. Campbell, “Portolan Charts,” 439–40.

24. Lanman, *Origin*, 19–21.

25. Cortés, *Arte of Navigation*, fol. lvi.

practical navigational tools in plotting and maintaining long, pelagic dead reckoning courses. Even on shorter coastal voyages, moreover, a chart may have been useful in providing information on the relative location and sequence of certain landmarks and maritime hazards, though this type of use would not necessarily have required that the charts be marked upon in any way.<sup>26</sup>

## OCEANIC NAVIGATION

Though portolan charts may have given late medieval pilots greater freedom, control, and confidence in plotting courses between ports throughout southern Europe, North Africa, and the Levant, the early charts were generally less useful for navigating outside the Mediterranean.<sup>27</sup> The farther one ventured beyond the Straits of Gibraltar, the more spotty and unreliable the charts' information was likely to be. As Genoese and Venetian merchant ships ventured into the North Sea and explored the western coast of Africa during the late thirteenth and early fourteenth centuries, Italian cartographers gradually incorporated those coastlines into their portolan charts.<sup>28</sup> Yet sailing on the Atlantic Ocean posed novel challenges that Mediterranean pilots did not have to face, and with which their traditional portolan charts were not designed to assist them.

The first serious shortcoming of the Mediterranean portolan charts was probably made manifest through Portuguese explorations of the Atlantic Ocean in the mid-fourteenth century. As the Portuguese undertook a systematic exploration of the African coast, supported and encouraged by their famed Prince Henry the Navigator,<sup>29</sup> they discovered a series of small islands strategically situated in the North Atlantic, including the Canaries, the Azores, and Madeira.<sup>30</sup> In order to take full advantage of their discoveries, the Portuguese decided to colonize the islands; but this, in turn, necessitated that Portuguese mariners be able to locate and return to them consistently. Navigation by dead reckoning, for which traditional portolan charts had been designed, might have worked well enough in the limited confines of the Mediterranean, where one was rarely out of sight of land for more than a few days at a time. But in the open ocean, over journeys of much greater distance and with no landmarks of any kind available for navigational reference, dead reckoning with a magnetic compass alone proved far less reliable and unsuited to the tricky task of locating small islands in a boundless sea.

In order to supplement their more traditional navigational knowledge, the Portuguese developed a new technique for confirming their ships' locations at sea: astronomical observation.<sup>31</sup> The idea of looking to the heavens for guidance was certainly not new to mariners, who had relied on the stars as a means of finding their bearings

long before the introduction of the magnetic compass (and would for a long time after). The Portuguese innovation, however, was to use the stars as a means of confirming the observer's position on the earth's surface, something that had previously been possible only with recourse to earthbound reference points or through the sort of rough estimation of distance traveled inherent to the traditional practice of dead reckoning.

During the last half of the fifteenth century, Portuguese pilots learned to use simplified versions of two ancient astronomers' tools: the quadrant and the astrolabe. By 1500, both instruments had been used by astronomers for centuries, and in their most highly developed forms they were designed to help astronomers with a number of complicated calculations.<sup>32</sup> Both were thoroughly mathematical in design—the heart of the astronomers' astrolabe always included a stereographic projection of the heavens—and required considerable mathematical mastery to use. Most of their basic functions were well beyond the mathematical understanding of practicing pilots; but at that time pilots had little need for astronomers' complex mathematical calculations. What

26. Campbell, "Portolan Charts," 440–46; Kelley, "Origins and Uses"; and chapter 7 in this volume.

27. See chapter 7 in this volume.

28. Waters, "Reflections," 286, and Boies Penrose, *Travel and Discovery in the Renaissance, 1420–1620* (Cambridge: Harvard University Press, 1952), 241–45.

29. The moniker "the Navigator" was not applied to Prince Henry until the nineteenth century, when it was popularized by the work of Richard Henry Major, *The Life of Prince Henry of Portugal, Surnamed the Navigator, and Its Results* (London, 1868; reprinted London: Frank Cass, 1967). Indeed, recent historiography has repeatedly pointed out that while Henry may have encouraged Portuguese Atlantic exploration, he never made any exploratory voyages himself and may well have had little knowledge or understanding of the navigational techniques he is supposed to have so fervently supported; see chapter 38 in this volume; W. G. L. Randles, "The Alleged Nautical School Founded in the Fifteenth Century at Sagres by Prince Henry of Portugal, Called the 'Navigator,'" *Imago Mundi* 45 (1993): 20–28; and Bailey W. Diffie and George D. Winius, *Foundations of the Portuguese Empire, 1415–1580* (Minneapolis: University of Minnesota Press, 1977), 113–22.

30. For a thorough, if somewhat one-sided, treatment of early Portuguese explorations of the Atlantic Ocean and the navigational and cartographic innovations stemming from that period, see *HPC*, 2:52–108; see also Diffie and Winius, *Portuguese Empire*, 123–43.

31. The Portuguese may have commissioned the help of a Majorcan cosmographer known as "Master Jacome," who is often identified as Jafuda Cresques, son of the Majorcan cosmographer and cartographer Abraham Cresques, though none of this is certain; see *HPC*, 2:95–97, and Diffie and Winius, *Portuguese Empire*, 115–18.

32. The early histories of the astrolabe and quadrant are somewhat obscure. The astrolabe was certainly an ancient Greek invention and was adopted by Arabic astronomers before the ninth century. The Arabs developed it into a highly sophisticated mathematical instrument, from which they also derived the astronomer's quadrant. The use of both instruments spread to astronomers in southern Europe during the tenth century and reached northern Europe in the eleventh. See Emilie Savage-Smith, "Celestial Mapping," in *HC* 2.1:12–70, esp. 24–28.





FIG. 20.3. THE TITLE PAGE FROM WAGHENAER'S *SPIEGHEL DER ZEEVAERDT*, 1584–85. The frontispiece depicts a number of common early modern navigational instruments, including the quadrant, astrolabe, cross staff, dividers, and box compass, all of which are depicted, respectively, from top to bottom along each side. Each of the male figures (on either side of the title itself) is holding a lead and line. Size of the original: 37 × 24 cm. Lucas Jansz. Waghenaer, *Spiegel der zeevaerdt* (Leiden: Christoffel Plantijn, 1584–85). Photograph courtesy of the James Ford Bell Library, University of Minnesota, Minneapolis.

pilots needed was a means of making a simple celestial observation—measuring the altitude of the sun or the Pole Star above the horizon—and the instruments they used were in effect stripped down to perform that one function. Over the next century, pilots throughout Europe adopted and learned to use these new mariners' instruments, and in the sixteenth century they added a third to their arsenal: the cross staff, possibly adapted from the Arab astronomers' *balestilha* or the *khashaba*, which was used by pilots in the Indian Ocean (fig. 20.3).<sup>33</sup>

Each of the altitude-measuring instruments had its own virtues and shortcomings, and pilots tended to prefer one over another for different tasks.<sup>34</sup> The quadrant was perhaps the easiest instrument to use in principle. It was comprised of a quarter-circle, scaled from zero to ninety degrees, with a pair of sights along one edge and a plumb

bob attached to its vertex (fig. 20.4). The observer located the star in question along the sighted edge, gazing from the circumference toward the vertex, while an assistant noted the angle to which the instrument was inclined according to the point where the plumb bob intersected the scaled circumference. The quadrant's major failing from a nautical point of view was that it had to be kept vertically stable. It was fine for observations taken on land (for example, in establishing the latitude of a port or cape), but it was very difficult to use accurately on the deck of a moving ship; for this reason, most pilots preferred to rely on the other two instruments. Moreover, because the ob-

33. Arab and Persian pilots sailing throughout the Indian Ocean had learned to navigate with reference to celestial altitudes long before their Western European counterparts, using instruments such as the *khashaba* to make their observations. This instrument probably consisted of a wooden board attached to a cord knotted at regular intervals. The pilot held the board so that its edges seemed to touch simultaneously the horizon and the star whose altitude was to be measured, and stretched the cord from the board to his eye. The number of knots in the length of cord could then be used to calculate the star's altitude, and hence the observer's north-south position. Earlier versions of the instrument most likely placed the knots at fixed locations on the cord rather than at equal intervals from one another, so each knot represented the altitude of the Pole Star for a given place. See Mājid al-Sa'dī, *Arab Navigation*, 317–19; Marina Tolmacheva, "On the Arab System of Nautical Orientation," *Arabica: Revue d'Études Arabes* 27 (1980): 180–92; James Prinsep, "Note on the Nautical Instruments of the Arabs," and H. Congreve, "A Brief Notice of Some Contrivances Practiced by the Native Mariners of the Coromandel Coast, in Navigating, Sailing and Repairing Their Vessels," both in *Instructions nautiques et routiers arabes et portugais des XV<sup>e</sup> et XVI<sup>e</sup> siècles*, 3 vols., trans. and anno. Gabriel Ferrand (Paris: Librairie Orientaliste Paul Geuthner, 1921–28), 3:1–24, esp. 1–8, and 3:25–30, esp. 26–28; and V. Christides et al., "Milāḥa," in *The Encyclopaedia of Islam*, 11 vols. plus supplement, glossary, and indexes, ed. H. A. R. Gibb et al. (Leiden: E. J. Brill, 1960–2004), 7:40–54, esp. 51.

Although early versions of the European cross staff may well have been based on older Islamic maritime instruments such as the *khashaba* (Taylor, *Haven-Finding Art*, 166, and Waters, *Art of Navigation*, 53–54), the Portuguese had long since developed their own techniques for celestial navigation using the mariner's astrolabe, independent of direct Islamic influences, when they made contact with Indian Ocean pilots in 1498. Arab navigators on the Mediterranean are an unlikely source for such techniques in Portugal, because they seem to have been as slow as their southern European rivals in adopting methods of celestial navigation for use on that sea (see Christides et al., "Milāḥa," 46–50). Likewise, Portuguese mariners appear to have derived their simplified astronomers' instruments not directly from Islamic sources, but rather from those of Western astronomers (for example, see Taylor, "Mathematics and the Navigator," 5–6, where the author describes Leonardo of Pisa's simplification of the quadrant).

34. For more detailed discussions of early modern instruments for making altitude measurements aboard ship, see Jean Randier, *Marine Navigation Instruments*, trans. John E. Powell (London: John Murray, 1980); Alan Stimson, *The Mariner's Astrolabe: A Survey of Known, Surviving Sea Astrolabes* (Utrecht: HES, 1988); Alan Stimson and Christopher St. J. H. Daniel, *The Cross-Staff: Historical Development and Modern Use* (London: Harriet Wynter, 1977); Bennett, *Divided Circle*, 27–37; May, *Marine Navigation*, 119–54; Hewson, *Practice of Navigation*, 73–98; and Waters, *Art of Navigation*, 39–77.

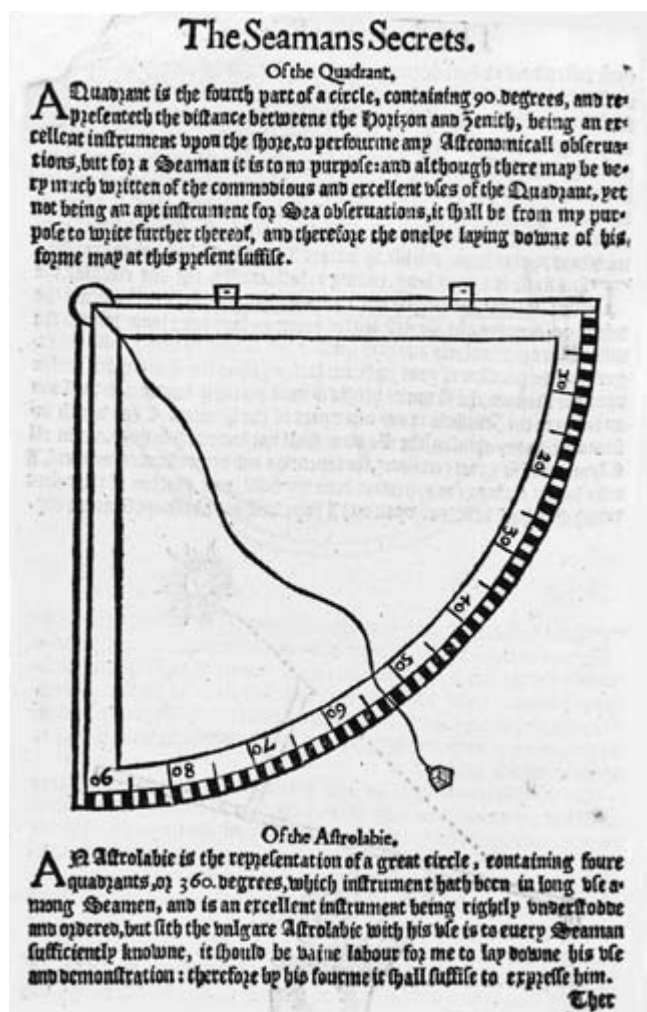


FIG. 20.4. DEPICTION OF A MARINER'S QUADRANT, LATE SIXTEENTH CENTURY.

Size of the original page: 18.7 × 14 cm. John Davis, *The Seamans Secrets* . . . (London: Thomas Dawson, 1595), MI verso. Photograph courtesy of the BL.

server necessarily had to stare at the object whose altitude he was trying to measure, the quadrant was more useful for sighting fixed stars, as opposed to the sun.<sup>35</sup>

The mariner's astrolabe was probably introduced at sea shortly after the quadrant. It was a very basic, skeletal variation on the ancient astronomer's version, consisting of little more than a scaled circle with a pivoting alidade. Whereas astronomers' astrolabes were solid circular plates (on which were engraved star charts, calendars, and calculation tables), the interior portion of the maritime version was left open so that the wind would not cause it to spin or swing as easily; it was often heavily weighted at the bottom for the same reason (figs. 20.5 and 20.6). To make an observation, the observer suspended the instrument vertically from a ring at the top and sighted the object through the twin sights mounted



FIG. 20.5. A TYPICAL MARINER'S ASTROLABE, OF SPANISH MANUFACTURE, 1563. This modest instrument is scaled down from its astronomical cousin.

Diameter of the original: 19.8 cm. Photograph © Musée des Arts et Métiers—CNAM, Paris / Photo Pascal Faligot—Seventh Square (inv. 3864-1).

on the alidade. He then noted the angle at which the alidade crossed the degree scale along the circumference of the circle. If he desired, he could even turn the instrument around and repeat the observation using the duplicate scale on the other side of the circle in order to check his initial measurement. Although stellar observations were possible, the need to suspend the instrument from above made it cumbersome compared with the quadrant or cross staff. However, the astrolabe was especially useful for making solar observations, especially those of high elevation (as at noon), for there was no need for the observer to stare into the sun. Instead, he could simply suspend the instrument so that the sun's rays shone through one sight and landed precisely on the pinhole in the other sight, and then read the angular elevation from the intersection of the alidade along the circumference (fig. 20.7).<sup>36</sup> As in the case of the quadrant, however, it could be very difficult to keep the astrolabe stable and vertical on the rolling deck of a ship at sea, especially in high winds.

35. Waters, *Art of Navigation*, 46–47.

36. Waters, *Art of Navigation*, 55–56.





FIG. 20.6. AN ASTRONOMER'S PLANISPHERIC ASTROLABE. In this case, a Flemish model from the sixteenth century. Diameter of the original: 16 cm. Photograph © Christie's Images Ltd. 1992.

Finally, the cross staff was composed of two perpendicular intersecting pieces, usually made of wood or ivory, the shorter of which slid freely along the longer. The observer held the end of the long staff to the corner of his eye, pointing it toward the star to be measured, and slid the cross vane (held vertically) back and forth until one end of it seemed to touch the horizon and the other touched the star. Then, holding the cross vane securely in place, the observer read from a scale marked on the longer piece the angular elevation of the star above the horizon (fig. 20.8). The cross staff was most useful for objects at lower altitudes, for in measuring higher altitudes it was difficult to see both ends of the cross vane at the same time. It also made solar observations difficult because, as in the case of the quadrant, the observer had to glance directly at the object he was observing. Many mariners compensated for this by attaching dark glass to one end of the cross vane or else by covering the sun with the cross vane and calculating the correction, but the process was still very difficult in practice. The cross staff was also of little use in the dark, when sighting the oceanic horizon was extremely difficult; it therefore worked best for stellar measurements made around dusk. The instrument's great advantage, however, was that it was much



FIG. 20.7. ILLUSTRATION OF A MAN MEASURING A SOLAR ALTITUDE USING A MARINER'S ASTROLABE. Pedro de Medina, *Regimie[n]to de nauegacio[n]: Contiene las cosas que los pilotos ha[n] e saber para bien nauegar . . .* (Seville: Simon Carpintero, 1563), fol. xv verso. Photograph courtesy of the Beinecke Rare Book and Manuscript Library, Yale University, New Haven.

easier to use with accuracy on a moving ship, because it was easier to hold in a stable vertical position. Toward the end of the sixteenth century, the English explorer John Davis invented a modified version called the back staff, which allowed the observer to make solar observations with his back to the sun, using the sun's shadow to indicate its altitude (fig. 20.9). This version proved very popular in the English navy and merchant marine, and continued in use for over a century.<sup>37</sup>

Once the pilot had measured the altitude of a given celestial object, he could use this datum to determine his own north-south position on the earth. At first the information was merely relative; the pilot used celestial observations to find his location only with respect to another known location, such as the port of Lisbon. Early quadrants, in fact, were not labeled with an angular scale of

37. Waters, *Art of Navigation*, 53–55 and 205–6.



FIG. 20.8. ILLUSTRATION OF A MAN MEASURING A STELLAR ALTITUDE USING A CROSS STAFF.

Pedro de Medina, *Regimie[n]to de nauegacio[n]: Contiene las cosas que los pilotos ha[n] e saber para bien nauegar . . .* (Seville: Simon Carpintero, 1563), fol. xxxv verso. Photograph courtesy of the Beinecke Rare Book and Manuscript Library, Yale University, New Haven.

degrees, but rather indicated the altitude of the Pole Star at various known locations. Eventually, pilots learned to convert this difference in celestial altitude into linear distances. Once a pilot knew the angular difference in the altitude of the Pole Star between his port of reference and his present location, he could multiply that number by a fixed number of miles (the linear distance represented by one degree of latitude), and thereby calculate his north-south distance from the port in question. The notion of latitude as one's geometrical position on a globe, known without reference to other fixed landmarks, was not part of the pilot's worldview until the end of the fifteenth century. As they explored farther south along the African coast, Portuguese pilots could no longer rely on the Pole Star for their observations, because it disappeared below the horizon. Around 1485, they learned instead to calculate their position using the altitude of the sun at noon and the solar declination for the date in question.<sup>38</sup> Waters has argued that this shift in celestial reference points



FIG. 20.9. AN IVORY BACK STAFF, ENGLISH, 1690. Typical of seventeenth-century models. Made by Thomas Tuttell. Photograph © National Maritime Museum, London (neg. no. D4504).

led pilots to conceive of navigating with respect to the stars alone rather than by means of earthbound reference points—in other words, to think geometrically in terms of latitude rather than in terms of linear distance from a known port.<sup>39</sup>

The utility of such observations in meeting the most pressing needs of Portuguese mariners was obvious: pilots were no longer dependent solely on dead reckoning by magnetic compass to guide their ships to hard-to-find islands in the Atlantic Ocean. Instead, having once located an island, the initial discoverers could use astronomical

38. Because the annual path of the sun, called the ecliptic, does not run parallel to the equator, on every day except for the two equinoxes (when the ecliptic crosses the equator) the sun is displaced north or south of the equator by a known angular distance. Because the equator is the pilot's geometrical reference point in measuring his north-south position, the sun's displacement from it must be accounted for in making his measurement.

39. Waters, "Reflections," 327–29. See also E. G. R. Taylor, "The Navigating Manual of Columbus," *Journal of the Institute of Navigation* 5 (1952): 42–54, esp. 45–46. The fact that solar declination tables were calculated with respect to the equator rather than a more mundane point of reference, such as a particular port, may support Waters's argument in favor of a new, geometrically based worldview.

observation to determine its north-south position. When other pilots sought to return to the same place, they could follow a course that would bring them to the island's latitude, several leagues to the east or west of their target. They could then maintain a constant easterly or westerly course, using the magnetic compass, and be certain of reaching their destination eventually.<sup>40</sup> If they strayed from their intended latitude along the way, further celestial observations would alert them and tell them how to correct the problem; by the early sixteenth century, the pilot's equipment included a set of tables that told him how far he would have to sail along various compass headings in order to increase or decrease his ship's latitude by one degree.<sup>41</sup>

Once pilots had learned to measure and think of their location on the earth in terms of angular measurement, they soon began recording their positions and routes in angular terms. The next logical step was for cartographers to take such measurements into account when drawing their charts. Early portolan charts were compiled primarily by using rough estimates of the linear distances between various points. Latitude measurements taken from astronomical observations were usually far more precise and eventually came to supplant traditional linear distances in the minds of cartographers as the true definition and determinant of one's location on earth (at least in the north-south direction). Portuguese cartography reflected this change: the first portolan charts that included a scale of latitude were made by the Portuguese in the late fifteenth or early sixteenth century, and came to be known as plane charts (plate 14).<sup>42</sup> The idea of latitude as a mark of location in cartography was not a new one; ancient cosmographers, most notably Claudius Ptolemy, had already carved the world into a gridlike pattern of latitude and longitude lines, locating all points within the grid by means of a two-coordinate system. But by the Middle Ages the technique had been forgotten in western Europe, only to be rediscovered in learned circles with the recovery and circulation of Ptolemy's *Geography* in the fifteenth century. Not until the Portuguese explorations of the late fifteenth century was the idea applied to practical cartography and navigation.

The radical innovation of this new way of seeing (and sailing) the world deserves to be stressed: cartographers, and the pilots who made use of their charts, no longer viewed the world only in terms of linear distance and direction; they began to perceive it more geometrically, in terms of angular distance as well. Most pilots did not embrace the change immediately, however; even the most numerate among them continued to be skeptical regarding navigation by latitude and longitude throughout the seventeenth century, in large part because they still lacked an accurate means of determining their longitude at sea, and also because the latitude and longitude data for ports

around the world were often inaccurate. Moreover, for the vast majority of voyages, which took place along well-established routes, traditional methods of navigation were still perfectly adequate. Nevertheless, the basic technique of sailing along the latitude of a given destination proved most useful for long-distance oceanic navigation and was the method on which Columbus relied in his quest to find a western route to the spice markets of Asia.<sup>43</sup>

A second limitation of the early Mediterranean-centered portolan charts was their failure to account for the magnetic variation of the compass. This phenomenon, first discovered during the fifteenth century but never well understood during the early modern period, involves a property inherent in all compasses to point to a position that is usually somewhat removed from true north. The deviation results from the fact that the earth's magnetic pole does not correspond perfectly with its geographical/astronomical pole. Nor is compass variation itself consistent; it can range from zero to more than twenty degrees, either east or west of true north, and also changes over long periods of time even with respect to the same geographic location, due to the earth's constantly changing magnetic field.<sup>44</sup> In using a navigational method as heavily dependent on magnetic direction finding as dead reckoning, compass variation can cause enormous confusion; its effect on charts compiled from compass-based observations was similarly corrupting.

On the Mediterranean Sea, magnetic variation created little difficulty for medieval pilots, in part because its effect on the region in this period was comparatively mild (probably nine to eleven degrees easterly variation). More important, because all medieval rutters and charts were used in conjunction with (and perhaps compiled using) uncorrected compass readings, they did not take the then-unknown effect of variation into account. The error was therefore a consistent one, causing the compasses, rutters, and charts to agree with one another.<sup>45</sup> But over longer voyages, such as the transoceanic explorations of Columbus and John Cabot, the effects of the phenomenon became more pronounced and varied and hence more

40. Luís de Albuquerque, "Astronomical Navigation," in *HPC*, 2: 221–357, esp. 221–28.

41. Waters has argued that these tables were simply more specialized versions of the medieval *toleta de marteloio* ("Reflections," 323–27).

42. Portuguese cartographers probably began making such charts around 1485, though all of the earliest surviving examples were most likely made between 1500 and 1510. See W. G. L. Randles, "From the Mediterranean Portulan Chart to the Marine World Chart of the Great Discoveries: The Crisis in Cartography in the Sixteenth Century," *Imago Mundi* 40 (1988): 115–18; Campbell, "Portolan Charts," 386; Waters, *Art of Navigation*, 67; and *HPC*, 2:216–19.

43. Waters, *Art of Navigation*, 76.

44. Waters, *Art of Navigation*, 24–26, and Taylor, *Haven-Finding Art*, 172–91.

45. Taylor, *Haven-Finding Art*, 172, and Waters, *Art of Navigation*, 76.



disconcerting for pilots. The growing navigational importance of Pole Star observations also called greater attention to the fact that celestial and compass observations usually did not agree.

Cosmographers, compassmakers, and mariners invented a number of means to correct for compass variation. The simplest involved reattaching the compass needle to its fly so that it would indicate true north for one's home port and nearby waters. For short voyages along well-known routes, this solution might have been adequate, but it could also lead to serious problems in relatively unknown waters. Many cartographers altered their charts to correct for the discrepancy between compass and celestial observations, sacrificing their charts' internal consistency in the process. Some charts of the Mediterranean, for example, used different latitude scales on their eastern and western edges, which were out of phase with one another by roughly  $5\frac{1}{2}$  degrees. Charts of the Atlantic Ocean sometimes took an even more radical approach, depicting a second equator at roughly a twenty-degree angle to the first, creating what has become known as the oblique meridian (plate 14). Such charts were admittedly useless for plotting trans-Atlantic courses, but this was not their purpose; rather, they were intended for navigating along both the European and North American coasts, assuming that pilots would simply follow a single latitude to get from one continent to the other.<sup>46</sup>

These cartographic discrepancies persisted throughout the sixteenth and seventeenth centuries, though they were severely criticized by cosmographers who urged instead that pilots make careful measurements of the compass variations throughout their voyages and that cartographers use their data to correct their charts accordingly. The Englishman William Borough, in his 1581 book *A Discours of the Variation of the Cumpas*, was particularly adamant about the need to measure and record compass variation and described several techniques for doing so. The easiest involved a new instrument, the compass of variation, which was simply a compass with a gnomon added to it (fig. 20.10). The pilot was supposed to check the compass bearing precisely at noon, when the sun was directly south of his position (or north, if he was in the southern hemisphere). The shadow cast by the gnomon would then point to geometric north (or south), and the angular difference between the shadow and the compass bearing would be the variation for that location. Though a number of mathematically minded explorers did make and record such observations, the device was not easy to use aboard a moving ship, and it does not seem to have been used by the vast majority of early modern pilots.

Traditional portolan charts carried one other serious limitation, which rendered them useless for navigation at more extreme latitudes (more than forty degrees, either north or south): they failed to account for the conver-

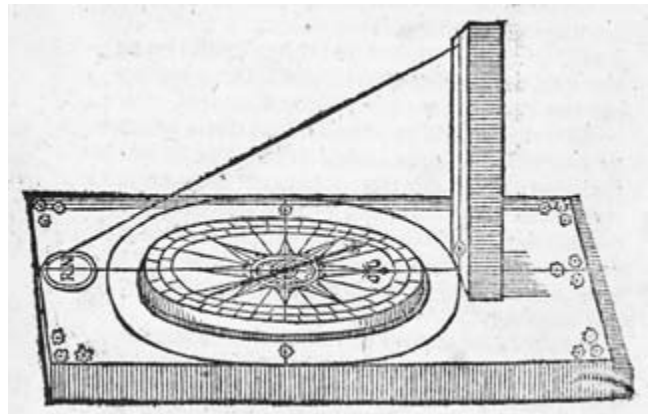


FIG. 20.10. A SIMPLE COMPASS OF VARIATION. Size of the detail: ca.  $6.5 \times 10.6$  cm. William Borough, *A Discours of the Variation of the Cumpas . . .*, pt. 2 of Robert Norman, *The Neue Attractiue: Containyng a Short Discourse of the Magnes or Lodestone . . .* (London: Ihon Kynngston, 1581), Bi verso. Photograph courtesy of the BL.

gence of meridians. Though historians disagree over precisely what projection, if any, was used to construct the earliest Mediterranean portolan charts,<sup>47</sup> they all implicitly assume (even when they do not explicitly delineate) a regular grid pattern composed of parallel latitude and longitude lines. In some cases, later users even added such lines to older charts that did not possess them originally. After the early years of the sixteenth century, once latitude scales had become a regular feature of oceanic portolan charts, the assumption of parallel meridians became even more deliberate and entrenched. Yet parallel meridians caused considerable cartographic difficulty, of

46. Waters, *Art of Navigation*, 67–70. See chapter 7 in this volume.

47. In seeking to determine the projection underlying early portolan charts, historians of cartography have attempted to impose a latitude and longitude grid even on charts that show no evidence of having been compiled with such geometrically based data in mind. Some, including Lanman (*Origin*, 2), have argued that the earliest charts were created according to a square grid pattern, while others have asserted that a rectangular grid was used. Nordenskiöld and Clos-Arceuduc have even argued that the earliest charts anticipated the Mercator projection by over a century, albeit accidentally, because they took as given the straight-line loxodromes, which are one of the Mercator projection's most notable and important features; see A. E. Nordenskiöld, *Periplus: An Essay on the Early History of Charts and Sailing-Directions*, trans. Francis A. Bather (Stockholm: P. A. Norstedt & Söner, 1897), 16–17, and A. Clos-Arceuduc, "L'énigme des portulans: Etude sur la projection et le mode de construction des cartes à rhumbs du XIV<sup>e</sup> et du XV<sup>e</sup> siècle," *Bulletin du Comité des Travaux Historiques et Scientifiques, Section de Géographie* 69 (1956): 215–31, esp. 217–28. Most cartographic historians now agree, however, that although early portolan charts usually imply a grid-like pattern of parallel latitude and longitude lines, no coherent projection was deliberately used in their creation. Later charts, those explicitly incorporating latitude and longitude scales, usually employed the square grid or plane projection invented by the Portuguese toward the end of the fifteenth century. See Campbell, "Portolan Charts," 385–86.

course, because on the three-dimensional surface of the earth (which the charts were intended to represent as usefully as possible) meridians converge toward the poles. Representing them as parallel lines forced cartographers to stretch and distort the coastlines depicted on their charts. For regions near the equator, the distortion was minimal, but in progressing farther north or south, the distortion got progressively worse. As a result, coastlines fifty degrees or more north or south of the equator were stretched almost beyond recognition, and certainly beyond the ability of pilots to rely upon them in plotting their courses.

For Spanish and Portuguese pilots, the problem was not so serious. Having established their equatorial trade routes to the New World and the East Indies, the Iberians rarely took their ships more than forty degrees from the equator in either direction, and their plane charts worked well enough for the regions in which they sailed. Northern European explorers, however, faced a very different situation. With virtually all of the British Isles located north of the fiftieth parallel, for example, English mariners were already beginning their voyages at the outer limits of a plane chart's useful capacity. Moreover, in their attempts to discover a northern route to the lucrative spice markets of Asia, English explorers regularly took their ships above seventy degrees north latitude during the last half of the sixteenth century, a region that did not even appear on most plane charts. Accordingly, English cosmographers struggled to find a cartographic solution that would be of some use to their pilots.

One innovation hit upon by the English mathematician Edward Wright was an application of the Mercator projection to nautical cartography. Although Gerardus Mercator's 1569 map of the world was the first map explicitly constructed using the projection that still bears his name, Wright claimed to have worked out the mathematical solution independently and was certainly the first to adapt it for use in navigation; the scale of Mercator's world map was far too small to be used in plotting accurate courses at sea.<sup>48</sup> The great innovation of the Mercator projection was that it maintained the plane chart's parallel grid pattern of latitude and longitude lines, but it altered the spacing between the latitude lines so that they grew farther apart toward the poles.<sup>49</sup> The ratio of the linear distance of one degree of longitude at any given degree of latitude was therefore maintained, compensating for the fact that at higher latitudes the longitude lines should have been converging, but were not shown as such on the chart. As a result, the coastlines at higher latitudes were still depicted as far larger than they would have appeared on the three-dimensional surface of a globe, but their relative proportions at any given latitude were preserved, and the location of all points of reference agreed with astronomical observation.

Another major advantage of Wright's nautical adaptation of the Mercator projection was that plotting accurate courses by dead reckoning actually became easier. On a normal plane chart, each rhumb line was meant to represent a single constant compass heading. The rhumb lines were always depicted as straight lines, and they therefore intersected each parallel meridian at a constant angle. On a spherical surface, however, with steadily converging meridians, a rhumb line could not be straight, but would actually spiral toward one of the two poles.<sup>50</sup> The geometrical violence of representing a spherical surface on a plane chart therefore created a sort of navigational paradox: following a single compass heading did not result in a straight-line course, an inaccuracy that could cause trouble in plotting longer journeys. On Wright's chart, however, the preservation of the linear distance ratios for every degree of latitude meant that rhumb lines could be depicted accurately as straight lines. The pilot could therefore calculate the true compass heading between any two points using only a straightedge.<sup>51</sup>

Yet even charts on the Mercator projection suffered from the same basic shortcoming as their planar predecessors: distortion of the coastlines became progressively more severe toward the poles, making it very difficult for mariners to read and use the charts at very high latitudes. For the extreme northerly sailing in which English (and later Dutch) explorers were increasingly engaging, an entirely new type of chart was required: the polar projection. Rather than using the equator as its principal reference point, and suffering increased coastal distortion as one moved farther away from it, the polar projection placed one of the earth's poles (in England, typically the north pole) in the center of the chart. Lines of latitude were cast as concentric circles, with the pole at their center, and meridians were depicted as radii of the circles. The polar projection was not without its own distortion; the farther one got from the pole at the center, the more warped and truncated the equatorial coastlines appeared. However, the polar projection was strongest precisely where more traditional charts were weakest: in the accurate and proportional depiction of coastlines at higher latitudes (fig. 20.11). English cartographers, especially the well-known polymath John Dee, experimented with the polar projection for most of the latter half of the sixteenth

48. Edward Wright, *Certain Errors in Navigation . . .* (London: Valentine Sims, 1599), opp. ¶¶¶; see also Waters, *Art of Navigation*, 215, 223.

49. Mathematically speaking, the space between any two latitude lines on a Mercator projection chart is proportional to the secant of the lines in question.

50. This effect was discovered by the renowned Portuguese cosmographer Pedro Nunes at the beginning of the sixteenth century; see Waters, *Art of Navigation*, 71–72.

51. Waters, *Art of Navigation*, 223–24.

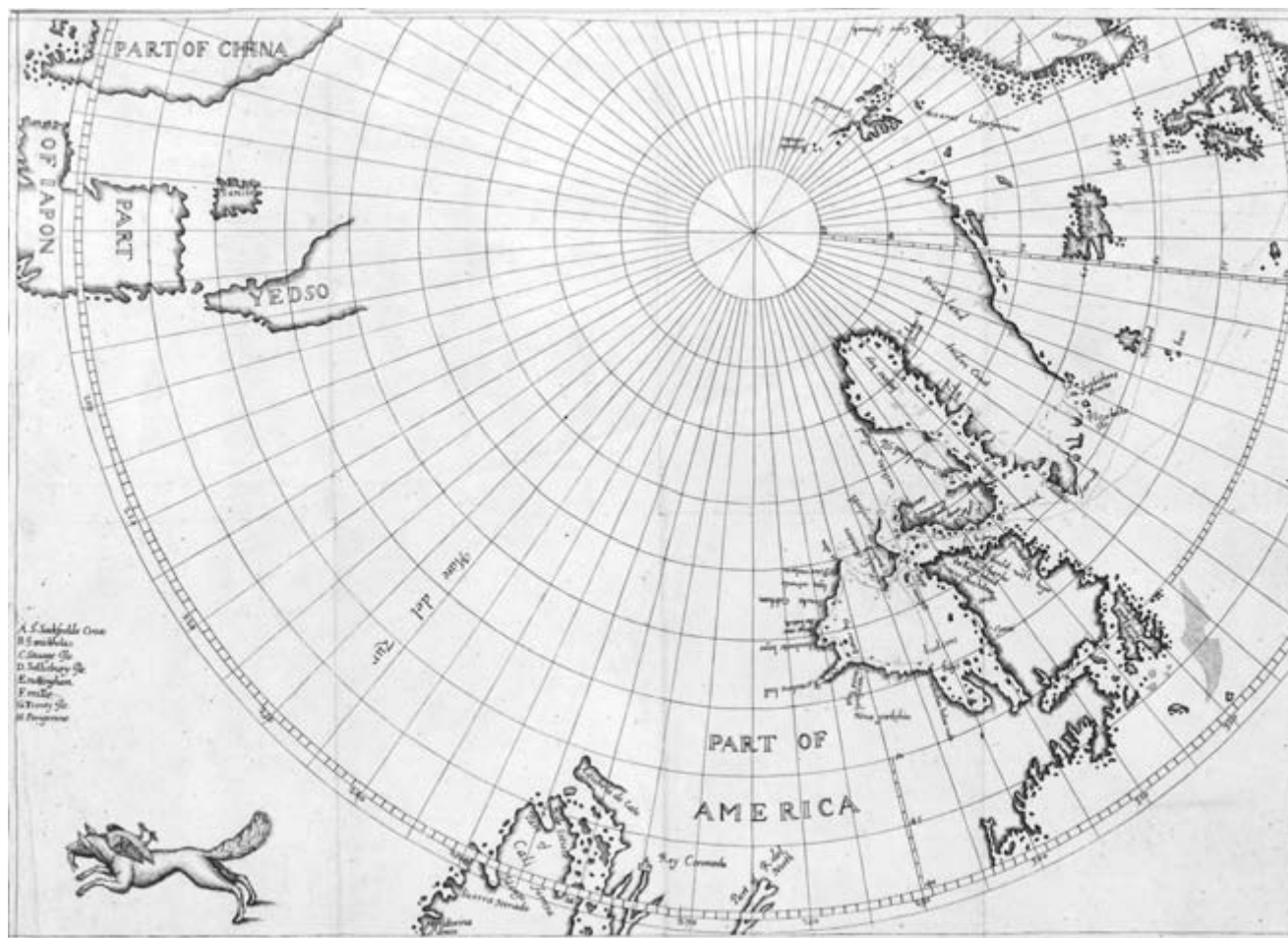


FIG. 20.11. A POLAR PROJECTION CHART OF THE NORTH ATLANTIC. The chart traces the 1631 attempt of Luke Fox to discover a northwest passage to Asia. Fox chose to use a circumpolar projection to depict the route of his voyage, he wrote, “for otherwise, another projection could not

have contained it but at unreasonable diversity” (A2 verso). Size of the original: ca. 31.8 × 44 cm. Luke Fox, *North-West Fox; or, Fox from the North-West Passage* (London: B. Alsop and T. Fawcet, 1635), chart inserted between preface and chap. 1. Photograph courtesy of the BL (G.7167).

century. Dee claimed to have invented the projection, in fact, calling it his “paradoxall compass”; he was probably unaware of Spanish experiments of a similar kind intended to create more accurate nautical charts of the southernmost tip of South America.<sup>52</sup> In any case, English explorers certainly started carrying polar projection charts as early as Martin Frobisher’s first voyage to Newfoundland in 1576.

#### NAVIGATIONAL TRAINING: LEARNING AND DOING

For centuries, the art of navigation was taught and learned only through years of direct personal experience at sea. Successful navigation throughout the Middle Ages depended entirely on the pilot’s intimate knowledge of the routes he sailed—the landmarks on which he relied for

guidance; the winds, tides, and currents with which he would have to contend; and the underwater hazards he could expect to encounter. This was the sort of information that could be learned only by sailing the routes in question over and over again under the close supervision and guidance of an experienced master pilot. Traditionally the extra training required to become a pilot (over and above the average mariner’s knowledge and skills) was open informally to a small number of young mariners who showed particular intelligence and promise at sea and who expressed an interest in learning the art. The incentive to become a pilot was high; as one of the ship’s officers, the pilot made considerably more money per voyage than the common mariner, and the most ambitious

52. Waters, *Art of Navigation*, 209–12.



pilots sometimes found opportunities to break into the ranks of the senior officer corps.<sup>53</sup>

During the early modern period, the aspiring pilot's training at sea was often arranged and accomplished on more formal terms than it had been in the past, through a lengthy apprenticeship negotiated by the boy's family. Many merchants, in particular, saw the advantage of having a younger son or nephew brought up to be a reliable and trustworthy ship's master and usually knew a number of experienced officers willing to take on an apprentice to make their employers happy.<sup>54</sup> In England, mercantile companies sometimes went so far as to mandate the training of their ships' junior officers, in order to ensure a ready supply of skilled pilots. In his 1553 instructions to the mariners in the employ of the Muscovy Company, England's first joint-stock trading company, the chief pilot Sebastian Cabot stipulated that "the gromals [grummets]<sup>55</sup> & pages [are] to be brought up according to the laudable order and use of the sea, as wel in learning of Navigation, as in exercising of that which to them appertaineth."<sup>56</sup>

Long experience at sea, though unquestionably vital for the success of a young pilot, nevertheless limited what could be taught. Running an early modern caravel was an enormously complex undertaking and required constant attention and labor on the part of all hands. The apprentice pilot certainly learned all he needed to know about tides and winds, spars and rigging, but most did not have time to study more learned and less immediately useful subjects such as reading and mathematics.<sup>57</sup> Nor would every ship necessarily have had someone aboard literate and numerate enough to teach them; even among senior officers, a surprising number could not read and write well enough even to sign their names.<sup>58</sup> Training a class of pilots who had the learning needed to handle some of the more complex new navigational instruments and techniques therefore created something of a paradox. The most talented and experienced mariners were by definition those who had spent most of their lives at sea and thus had had little or no opportunity to acquire the more formal education necessary for full mastery of the more theoretical aspects of mathematical and astronomical navigation. Moreover, experience-based education also tended to be highly conservative and resistant to even important innovations. The apprentice, after all, could learn only what his master understood well enough to teach him. The introduction of new techniques and technologies to the traditional and conservative art of navigation therefore required some sort of intervening impetus external to the apprenticeship itself.

In Spain and Portugal, the need for extranautical instruction led to the official establishment of formal training centers. During the late fifteenth century, the Portuguese Casa da Índia of Lisbon began to employ a num-

ber of cosmographers responsible for making, correcting, and approving both nautical charts and books of sailing directions for use by the pilots employed by the Casa. We may reasonably assume that the cosmographers probably also had a hand in teaching Portuguese pilots how to use the new mathematically based technologies they were providing. Far better known to historians, however, is the cosmographical school maintained by the Spanish, the Casa de la Contratación in Seville. Beginning in 1508, the Spanish Casa employed its own corps of cosmographers responsible for training, examining, and licensing all pilots who sailed in the service of the vast Spanish navy or merchant marine. As in the case of their Portuguese counterparts, they were also supposed to examine and approve all nautical charts and navigational instruments sold in Spain.<sup>59</sup>

As aboard ship, training through the Casa de la Contratación was informal at first. Given that one of the Casa's principal officials, the pilot major, was responsible

53. On the origins and training of early modern mariners, pilots, and officers, see G. V. Scammell, "Manning the English Merchant Service in the Sixteenth Century," *Mariner's Mirror* 56 (1970): 131–54; Kenneth R. Andrews, "The Elizabethan Seaman," *Mariner's Mirror* 68 (1982): 245–62; and Pablo Emilio Pérez-Mallaína Bueno, *Spain's Men of the Sea: Daily Life on the Indies Fleets in the Sixteenth Century*, trans. Carla Rahn Phillips (Baltimore: Johns Hopkins University Press, 1998), 63–98 and 229–37.

54. Scammell, "English Merchant Service," 139–46, and Andrews, "Elizabethan Seaman," 256–58.

55. While the original reads "gromals," the only entries in the *Oxford English Dictionary* that even vaguely match this word are "gromaly," "gromel," "gromil," and "grummel," all of which are listed as obscure forms of "gromwell," a plant with hard, stony seeds. "Grummet," however, is defined as "a ship's boy; a cabin-boy; the boy required to form part of the crew of every ship formerly provided by the Cinque Ports" (*Oxford English Dictionary*, 2d ed., 20 vols. [Oxford: Clarendon, 1989], s.v. "grummet"). This appears to be the most likely meaning of the term as used by Cabot.

56. Sebastian Cabot, "Ordinances, instructions, and aduertisements of and for the direction of the intended voyage for Cathaye . . .," in *The Principall Navigations, Voiages and Discoveries of the English Nation*, by Richard Hakluyt, 2 vols. (Cambridge: Cambridge University Press, 1965), 1:259–63, esp. 260.

57. Pérez-Mallaína Bueno, *Spain's Men of the Sea*, 78–79.

58. Early modern literacy rates have long been a source of debate among historians. Using documents from lawsuits heard at the Casa de la Contratación, and looking particularly at the presence or absence of required signatures from 798 mariners, Pérez-Mallaína Bueno has suggested that 79 percent of common sailors and roughly 50 percent of junior officers did not know how to sign their names. Surprisingly, the same was apparently true for 17 percent of ship's masters and 26 percent of (presumably licensed) pilots (*Spain's Men of the Sea*, 229–31). Given that the ability to sign one's name was not necessarily indicative of practical literacy, one may speculate that the true rate of illiteracy was even higher.

59. Clarence Henry Haring, *Trade and Navigation between Spain and the Indies in the Time of the Hapsburgs* (Cambridge: Harvard University Press, 1918), 35–39 and 298–316, and Waters, *Art of Navigation*, 62. See also chapter 40 in this volume.

for examining and licensing all pilots in the Spanish fleet, it was natural that he should become a source of instruction for those hoping to pass the exam, and his students often paid him a small fee for the privilege. Over time, however, and in part to avoid the conflict of interest inherent in having the pilot major serve as both the paid instructor and the examiner of aspiring pilots, the Casa instituted a formal lecture course designed to teach basic astronomy, cosmography, and mathematics, as well as practical piloting skills. The lectures were delivered by one of the cosmographers employed at the Casa and were required of all mariners hoping to take the pilot major's exam. Experience at sea was still crucial, of course; before sitting for the lectures, a would-be pilot had to prove that he had spent several years at sea, had a thorough empirical knowledge of the routes he intended to navigate, and had already mastered some of the more basic techniques of the art of navigation. The lectures at the Casa were meant to supplement the empirical training of talented and experienced mariners, providing them with the more theoretical instruction that most would not have had an opportunity to acquire at sea.<sup>60</sup>

Other countries, jealous in part of the enormous wealth Spain and Portugal had been able to acquire through their maintenance of global trading and colonial empires, hoped to duplicate their success by emulating institutions such as the Casa de la Contratación. Stephen Borough, an English pilot renowned for his Arctic exploration during the 1550s, spent a few years at the Spanish Casa as an honored guest after his return from the Arctic and developed a great respect for Spanish navigational acumen. Once back in England, he led a small crusade during the early 1560s to found a similar training and licensing institution under an English pilot major (probably realizing that he would be the most likely candidate for such a post). Although Borough failed in creating an English version of the Casa, he nevertheless had a profound impact on the training of London-area pilots until his death in 1584.<sup>61</sup> His dream did not perish with him; Thomas Hood's London mathematical lectures (1588–92) were delivered in the vernacular and addressed mathematical topics of practical concern, including the art of navigation. They were formally mandated by the Elizabethan Privy Council and funded by the aldermen of the city of London, many of whom were prosperous merchants with a great financial stake in the well-being of the English merchant marine.<sup>62</sup> The lectures offered years later at Gresham College, founded in 1598, continued the tradition of English-language mathematical education focused on practical endeavors.

In addition to formal instruction, the sixteenth century saw the publication of a multitude of practical manuals of navigation, which varied greatly in their pedagogical sophistication, mathematical content, and focus on actual

nautical practice. The earliest of these instructional manuals was compiled by the Portuguese cosmographer José Vizinho in the 1480s and was called "Regimento do astrolabio e do quadrante." The oldest surviving printed edition (now known as the Manual of Munich) was published in 1509 and includes instructions for finding the altitudes of the sun and the Pole Star, rules for "raising the pole" (increasing one's latitude) by one degree, a calendar and table of solar declination, and a translation of Johannes de Sacrobosco's *Sphaera mundi*.<sup>63</sup> The "Regimento" was followed in the mid-sixteenth century by the works of Pedro de Medina and Martín Cortés, both cosmographers of the Spanish Casa de la Contratación, whose manuals proved to be quite popular; both were translated into other languages and frequently reprinted.<sup>64</sup> Other manuals soon followed, written and published throughout Europe, which grew increasingly mathematically oriented. A key feature of virtually all such manuals was a section on the use (and sometimes on the construction) of the nautical chart; Cortés and the Englishman William Bourne, for example, gave very clear instructions on how to make and use the traditional plane chart.<sup>65</sup> Like the charts themselves, these cartographic chapters became increasingly sophisticated. Thomas Hood, in publishing some of his London lectures, expanded and refined Bourne's instructions,<sup>66</sup> while the English explorer John Davis actually introduced his readers to the finer points of mathematical navigation using a globe.<sup>67</sup> Edward Wright, in his 1599 instructional man-

60. Ursula Lamb, "The Teaching of Pilots and the *Chronographia o Repertorio de los Tiempos*," in *Cosmographers and Pilots of the Spanish Maritime Empire*, by Ursula Lamb (Brookfield, Vt.: Variorum, 1995), item VIII; Alison Sandman, "Cosmographers vs. Pilots: Navigation, Cosmography, and the State in Early Modern Spain" (Ph.D. diss., University of Wisconsin, 2001), 92–211; Haring, *Trade and Navigation*, 298–305; and Taylor, *Haven-Finding Art*, 174.

61. Eric H. Ash, *Power, Knowledge, and Expertise in Elizabethan England* (Baltimore: Johns Hopkins University Press, 2004), 87–134, and Waters, *Art of Navigation*, 103–8 and 513–14.

62. Ash, *Power*, 135–85, and Waters, *Art of Navigation*, 185–89.

63. M. W. Richey, "Navigation: Art, Practice, and Theory," in *The Christopher Columbus Encyclopedia*, 2 vols., ed. Silvio A. Bedini et al. (New York: Simon and Schuster, 1992), 2:505–12, esp. 509. See also Luís de Albuquerque, "Portuguese Books on Nautical Science from Pedro Nunes to 1650," *Revista da Universidade de Coimbra* 32 (1986): 259–78.

64. Pedro de Medina, *Arte de nauegar en que se contienen todas las reglas, declaraciones, secretos, y auisos, q[ue] a la buena nauegacion[n] son necessarios, y se deue[n] saber . . .* (Valladolid: Francisco Fernandez de Cordoua, 1545), and Cortés, *Breue compendio*.

65. Bourne, *Regiment for the Sea*.

66. As, for example, in Thomas Hood, *The Marriners Guide*, a short dialog that Hood published as a supplement to his edition of Bourne's *Regiment for the Sea . . .*, new ed., corrected and amended by Thomas Hood (London: Thomas Est, 1592).

67. John Davis, *The Seamans Secrets . . .* (London: Thomas Dawson, 1595).

ual, explained not only the use of the Mercator projection chart but its mathematical construction as well.<sup>68</sup> Many of these authors, including Hood, Davis, and Wright, included actual charts of the North Atlantic in their manuals for use in working out example calculations and perhaps in actual practice at sea.

### MATHEMATICAL NAVIGATION: THEORY AND PRACTICE

The increasing mathematical complexity and sophistication of sixteenth- and seventeenth-century navigation manuals raises some important questions. Just how much of the new, mathematically based art of navigation were practicing pilots absorbing and using at sea? How willing were they to abandon traditional methods and instruments for mathematical innovations? Were their mathematical capabilities strong enough to allow them to use the new technologies? In order to make full use of the new charts and instruments with which cosmographers supplied them, pilots needed to have a working knowledge of arithmetic, geometry, and trigonometry, and to be able to make accurate and precise astronomical observations from the deck of a moving ship. Yet in 1600 the average mariner was not necessarily comfortable with even the most basic arithmetical calculations, let alone trigonometry.

Nor is it clear that all authors of sixteenth-century navigation manuals even intended their work to be read by an audience of maritime practitioners, a great many of whom were illiterate in any case. Some manuals, such as those of Cortés and Bourne, seem to make a concerted effort to present complex material to a relatively unlearned, practically minded readership. Yet others, such as William Borough's short treatise on correcting for the magnetic variation of the compass, though claiming to be intended for the use of "all Seamen & Traueilers, that desire to bee cunning in their profession,"<sup>69</sup> probably appealed in actuality to only a small readership of skilled mathematicians. Borough, for example, frequently cited definitions and theorems from Euclid's *Elements* by number only, and also assumed a thorough grasp of spherical trigonometry in his readers, at a time when most mariners still found long division beyond their abilities (fig. 20.12). Still other authors, such as Thomas Hood and Thomas Blundeville, adopted a style and tone in their works that often appear to be more appropriate for the courtly and gentlemanly classes of Elizabethan London than for any actual navigational practitioners who inhabited a ship's cabin.<sup>70</sup>

In fact, many authors of early modern navigational manuals seem to have been less concerned with nautical practice per se than with mathematical sophistication for its own sake. Some had never even been to sea themselves

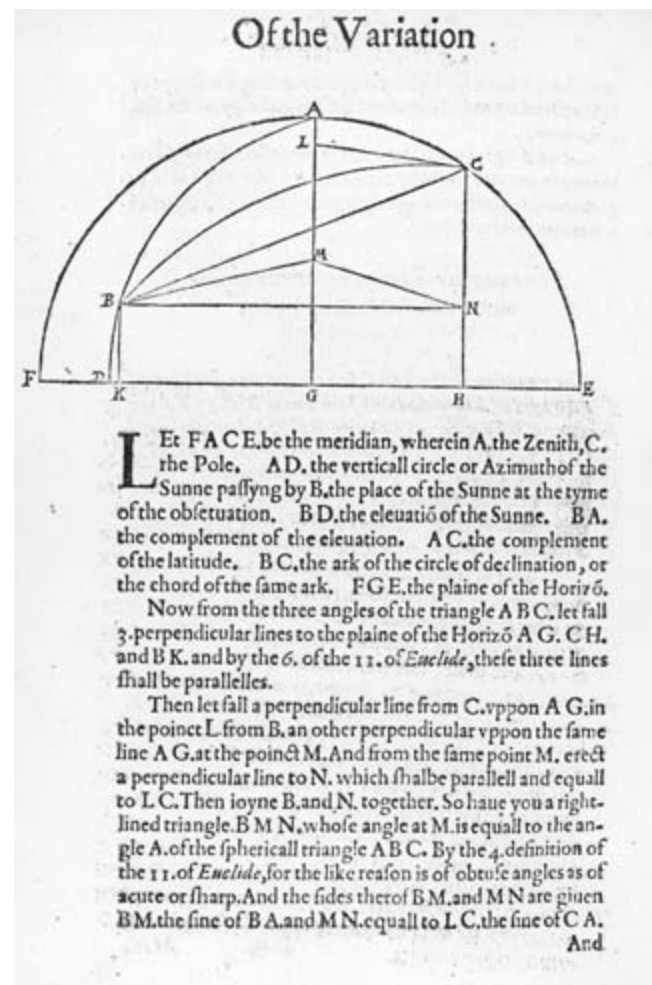


FIG. 20.12. A TYPICAL PAGE FROM WILLIAM BOROUGH'S *A DISCOVRS OF THE VARIATION OF THE CUMPAS*, 1581.

Size of the original page: ca. 17.9 × 11.5 cm. William Borough, *A Discovrs of the Variation of the Cumpas* . . . , pt. 2 of Robert Norman, *The Newe Attratiue: Containyng a Short Discourse of the Magnes or Lodestone* . . . (London: Ihon Kyngston, 1581), Dii. Photograph courtesy of the BL.

except as passengers (if indeed they had ever been to sea at all), and some of their suggested innovations would never have been practicable aboard ship. The apparent diversity of the navigation manuals' intended audience raises doubts about how many practicing pilots were able, or meant, to learn the lessons the manuals' authors purported to teach. Were mathematicians and cosmogra-

68. Wright, *Certaine Errors*.

69. William Borough, *A Discovrs of the Variation of the Cumpas* . . . , pt. 2 of Robert Norman, *The Newe Attratiue: Containyng a Short Discourse of the Magnes or Lodestone* . . . (London: Ihon Kyngston, 1581), iij verso.

70. Thomas Blundeville, *M. Blundeville His Exercises, Containyng Sixe Treatises* (London: John Windet, 1594).



phers presenting their work to men who used it at sea, or were they merely talking to one another while mariners maintained the same age-old practices they had always used?

In considering such an issue, one must first distinguish between two different types of pilot: the explorer and the pilot of an average merchant vessel. In the maritime history of most European states, virtually all of the best-documented early modern voyages had some sort of special status; often, the pilots were venturing into a particular area for the first time. Their navigational needs were therefore much greater than the average pilot's. In addition to being able to locate their vessels and plot their courses in unknown and uncharted seas, explorers were also expected to keep careful track of where they went and how they got there, so that the voyage could be repeated if it should prove profitable. The records of preparation for such voyages often featured the purchase of expensive navigational equipment, and sometimes special instruction for the voyages' pilots,<sup>71</sup> but the unusual requirements of their missions make it unwise to extrapolate such precautions to every mercantile voyage undertaken during the same period. The vast majority of pilots continued to follow exactly the same trade routes their predecessors had followed for decades or centuries, and they continued to learn all that they needed to know through the traditional means of oft-repeated empirical experience. Whether or not the average merchant marine pilot had any pressing need for the astronomical and mathematical innovations developed by land-bound mathematicians and cosmographers is therefore open to debate.

Fortunately, the bureaucratic nature of the Casa de la Contratación and other institutions promoting navigational innovation occasionally allows the historian to hear the pilots speaking in their own voices regarding the types of training they found most useful or the appropriateness of various technologies for use at sea. The cosmographers of the Casa and the pilots they trained and examined were often at odds with one another, and such controversies sometimes provided the pilots with a rare forum for expressing and recording their views of the art they practiced. Sandman, for example, has examined the numerous debates that took place during the sixteenth century between the Casa's cosmographers and pilots regarding the proper nature of navigational training offered at the Casa. The cosmographers sought to convince the pilots to alter their traditional practice at sea and to view navigation as a theory-based, mathematical science rather than a mere empirical craft.<sup>72</sup>

While the pilots outwardly maintained a conservative stance throughout the century, Sandman demonstrates that they nevertheless made important alterations over time in their actual practices at sea, a fact obscured by

their conservative rhetoric. Though they never acceded to the cosmographers' mathematical demands, over decades the pilots quietly redefined what it meant to be a well-trained pilot. Their emphasis remained firmly on practical experience over theoretical training, but the meaning of practical experience was gradually broadened to include many of the astronomical and cartographic techniques that the cosmographers had long urged them to adopt.<sup>73</sup> Based on the Spanish pilots' somewhat malleable notion of practical experience, we may safely conclude that at least some of the more basic mathematical advances to the art of navigation eventually made their way aboard ship. Such a conclusion is supported by William Bourne's contemporary statement (1580) regarding the adoption of new techniques among sixteenth-century English pilots:

I haue knowen within this .20. yeares that them that were auncient masters of ships hath derided and mocked th[em] that haue occupied their Cards and Plats, and also the obseruat[ion] of the altitude of the Pole [Star], saying that they care not for their Sheepes skins, for hee could keepe a better account upon a boord.

And when that they did take the latitude, they would cal them starre shooters and Sunne shooters, and would aske if they had stricken it. *Wherefore now iudge of their skilles, considering that these two poyntes is the principal matters in Nauigation.*<sup>74</sup>

On the other hand, while many pilots were not so conservative that they would never consider altering their practices to incorporate useful mathematical innovations, they often had strong opinions as to which innovations were most useful for their purposes. Astronomical observations and the use of charts with latitude scales both became standard practice in the Spanish merchant marine, for example, but correcting for the magnetic variation of the compass was a more difficult sell for the cosmographers. Practicing pilots were generally in favor of the simplest and most basic methods, such as altering the compass needle and fly so that the compass would indicate true north in home waters. Cosmographers at the Casa bitterly criticized such methods as being ad hoc and theoretically unsound, but their preferred method of making

71. As, for example, in the case of Hugh Willoughby's and Richard Chancellor's exploration of the Russian Arctic in 1553 or Martin Frobisher's voyages to Newfoundland in 1576–78. Special navigational equipment was purchased for the pilots by the sponsors of each voyage, and the ships' masters and pilots received navigational instruction from English cosmographers and mathematicians, including John Dee. See Ash, *Power*, 87–134.

72. Sandman, "Cosmographers vs. Pilots," 92–211.

73. Sandman, "Cosmographers vs. Pilots," 289–90.

74. William Bourne, *A Regiment for the Sea* (London: T. East, 1580), B.ij verso, emphasis added.

careful magnetic and astronomical observations and calculating the variation accordingly would have forced pilots to carry extra equipment and undertake a great deal of observational labor and complicated calculation. The issue came to a head during the 1540s regarding the use of charts with double latitude scales and oblique meridians. Cosmographers attacked these innovations as mere crutches—physically impossible and mathematically unsound, unreflective of reality, and indicative of a pilot who did not truly understand the basic theoretical underpinnings of his art. For their part, pilots were far less concerned with mathematics and the accurate reflection of reality than they were with safety and ease of use. They argued that it was far easier for them to continue using two-scale charts than it was for them to worry about correcting for a confusing and poorly understood phenomenon. They asked the cosmographers to allow them to keep the charts to which they had long been accustomed and on which they had learned to rely.<sup>75</sup>

### CONCLUSION

Because early modern mariners seldom left personal records of their activities at sea, it can be very difficult for the historian to piece together exactly what instruments and techniques they used in guiding their ships from one port to another. We know from ships' inventories that nautical charts were an increasingly common component of an early modern pilot's basic equipment and that pilots were usually expected to possess more than one chart on any given voyage.<sup>76</sup> We know from the curriculum of instruction at places like the Casa de la Contratación in Seville,<sup>77</sup> and from the many chapters devoted to the subject in countless editions of navigation manuals published throughout western Europe,<sup>78</sup> that pilots were expected to know how to use (and even make) their charts. And yet the many surviving examples of the charts themselves may lead the historian to question their actual use at sea, for most of them bear no mark or physical sign of ever having been used to plot a course.<sup>79</sup> The pilots themselves testified that they could not and did not rely on the Casa's officially prepared charts for their voyages, though these

seemingly conservative pilots objected not to the use of nautical charts per se but only to the use of those charts from the Casa that they considered inaccurate and too difficult to use.<sup>80</sup> The question is made more complicated by the considerable spectrum of mathematical talent and ability possessed by various pilots, from the illiterate and innumerate pilots who probably filled the ranks of most early modern merchant marines to mathematically gifted pilots and cosmographers such as John Davis and William Borough.

Although we may never be able to reconstruct completely early modern navigational practice, and especially the use of nautical charts at sea, we can nevertheless be certain that most pilots did take at least some charts aboard ship; that the charts' scaled depiction of a large, open nautical space probably facilitated the plotting of longer, pelagic courses during which the pilot would have no recourse to land-based reference points; that advances in maritime practice (such as the introduction of astronomical observations to confirm a ship's position) had an important impact on the evolution of nautical cartography; and that the difficulties faced by early modern maritime explorers created a series of navigational and cartographic challenges, most of which were eventually overcome by mathematicians and cosmographers, whether or not most contemporary practicing pilots were able to take full advantage of their most sophisticated solutions.

75. Alison Sandman, "Mirroring the World: Sea Charts, Navigation, and Territorial Claims in Sixteenth-Century Spain," in *Merchants & Marvels: Commerce, Science, and Art in Early Modern Europe*, ed. Paula Findlen and Pamela H. Smith (New York: Routledge, 2002), 83–108; Ursula Lamb, "Science by Litigation: A Cosmographic Feud," in *Cosmographers and Pilots of the Spanish Maritime Empire*, by Ursula Lamb (Aldershot: Variorum, 1995), item III; and Pérez-Mallaína Bueno, *Spain's Men of the Sea*, 232–37.

76. Campbell, "Portolan Charts," 439–43.

77. Haring, *Trade and Navigation*, 298–304, and Sandman, "Cosmographers vs. Pilots."

78. For example, Cortés, *Arte of Nauigation*, fols. lvi–lxl verso and lxxx verso–lxxxix, and Bourne, *Regiment for the Sea* (1574), 49–51.

79. Campbell, "Portolan Charts," 443–44.

80. Sandman, "Mirroring the World," and chapter 40 in this volume.