The Premedieval Origin of Portolan Charts: New Geodetic Evidence

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Abstract: Portolan charts are highly realistic medieval charts that show remarkably accurate coastlines of the Mediterranean and the Black Sea. They emerged suddenly, without any predecessors or a clear developmental path, in Italy during the thirteenth century. There is broad scholarly agreement that these charts are original creations of European medieval culture. However, corroborating evidence is lacking, and a convincing explanation of the method of their construction has so far not been provided. In this essay it is demonstrated by means of geodetic analysis that the overall shape of the coastlines corresponds closely to that on a modern map based on the Mercator projection. It is further demonstrated that this correspondence cannot possibly be due to chance. Consequently, the existence of a Mercator or Mercator-like map projection on portolan charts is incompatible with the assumed medieval origin of these charts. Portolan charts are far more sophisticated than has hitherto been recognized. Their construction was well beyond the capabilities of cartographers from either medieval Europe or the Arabic-Islamic world. This conclusion serves to reopen the question of the origins of the geometric data and the construction methods that until now have appeared to underlie medieval portolan charts.

KEY QUESTIONS

The earliest extant portolan chart, known as the Carte Pisane, is conventionally dated to the end of the thirteenth century and shows the Mediterranean area with proportions that are essentially correct.[1] Portolan charts are far superior to the contemporary *mappaemundi* of the European intellectual clerical elite and to contemporary Arabic-Islamic maps in the realism with which they render the coastlines of their core area, which consists of the Mediterranean, the Black Sea, and the Atlantic coast from Cap Drâa in present-day Morocco up to and including the south coast of England. Portolan charts are far more accurate than, and share no characteristics with, the highest cartographic achievements known from antiquity,

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[1] The Bibliothèque Nationale de France, owner of the Carte Pisane (Departement des Cartes et Plans, Res. Ge. B1118), postulates the end of the thirteenth century. See also Tony Campbell, "Census of Pre-Sixteenth-Century Portolan Charts," *Imago Mundi*, 1986, 38:67–94. Ramon Pujades has recently attempted to make a case for an early fifteenth-century origin: Ramon J. Pujades i Bataller, "The Pisana Chart: Really a Primitive Portolan Chart Made in the Thirteenth Century?" *Bulletin du Comité Français de Cartographie*, 2013, *216*(6):17–32.

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Claudius Ptolemy's scientifically designed maps. They appear to be entirely unrelated to any known cartographic tradition.

The medieval origin of the surviving portolan charts is not disputed. It is the origin of the geometric information on those charts—that is, the shape of the coastlines—that is the subject of this essay. The accuracy of these charts leaves no doubt that they are based on geometric measurements rather than on a mental image of the Mediterranean world, as is the case with *mappaemundi* and contemporary Arabic-Islamic maps.

While consensus holds that portolan charts are original European medieval creations, a number of questions relevant to the history of science have not yet received a satisfactory answer. On what geometric measurement data are these charts based, how was this data collected, and how did it attain the necessary accuracy? How did medieval cartographers construct portolan charts from the underlying measurement data? What knowledge and technology are required to make such accurate charts, including and in particular their apparent map projection? Any answers to those questions will have to be reconciled with the state of science and technology in the medieval period.

The most enigmatic aspects of these charts are their accuracy and their close resemblance to a modern map based on the Mercator map projection or the equirectangular projection. The difference between these two map projections will be discussed later in this essay. A map projection may be described as a mathematical relationship between the coordinates on the sphere (latitude and longitude) and map coordinates (X and Y). Any representation of a portion of the spherical earth on a flat surface may be said to involve some kind of projection, but *geodetic-cartographic* map projections are designed to minimize— or, rather, control—the inevitable distortions, according to some criterion. There are map projections that render all meridians true to scale; others render small shapes without distortion; and yet others show the areas of countries and regions in their correct relative size.

The relevance of the questions I have posed is demonstrated by the fact that the Mercator projection was only introduced in 1569, by the Flemish cartographer Gerard Mercator. The science of geodesy had yet to be invented when the portolan charts first came into use, and the geodetic technique of triangulation, which was used in the eighteenth century to construct the geometric framework of the first scientifically produced topographical map, now known as the Cassini map of France, was still more than three centuries away. The hypothesis of portolan charts' medieval origin requires a convincing explanation for the gap that exists between the state of medieval science and technology (as far as this is known), on the one hand, and the requirements for scientific mapping of the large area portrayed by portolan charts, on the other.

PORTOLAN CHARTS: CHARACTERISTICS, FACTS, AND SCHOLARLY VIEWS

Serious research into the origin of portolan charts began in the middle of the nineteenth century, and a number of diverse hypotheses as to their origin and the method of their construction have since been proposed. The different points of view have converged to a consensus that postulates a medieval origin and assumes that the charts were drawn from measurements of compass bearings and estimates of distances sailed made by medieval mariners during trading voyages. Although this view is often presented as an established fact to the world beyond the small communities of medievalists and map historians, corroborating evidence is lacking and hardly any aspect of this hypothesis has ever been properly tested. The origin of portolan charts has therefore remained a matter of speculation. I have recently completed a critical review of the constituent aspects of the hypothesis of a medieval origin and have tested its geodetic aspects using quantitative methods.[2] A full geodetic analysis of these charts had not been available before my study. The results are surprising: the hypothesis of a medieval origin for portolan charts must be rejected unequivocally; the depiction of the coastlines on portolan charts cannot have a medieval origin. The implication is that these charts are copies of older maps or charts. Portolan charts cannot be falsifications made at some later date: there are simply too many surviving charts and their impact on later cartography is too clearly evident.

Only a short summary of the characteristics of portolan charts can be provided here. Portolan charts are manuscript charts drawn on vellum, a fine-quality parchment. The dimensions of a typical portolan chart showing the entire Mediterranean and Black Sea, and often the Atlantic coast, are determined by the dimensions of the skin. They are typically about 100 cm x 75 cm; thus the scale of the charts is approximately 1:5.5 million—that is, 1 cm on the chart equates to approximately 55 km in the real world. The names of ports and coastal landmarks are written along and at right angles to the coastline, on the side of the land. The coastline itself consists of a single line of black ink. The charts have no preferred orientation; in order to read all the toponyms one has to rotate the chart. From their cartographic content it is clear that portolan charts are nautical charts, a new type of map at the time of their appearance. Although many surviving portolan charts appear to have been objects intended for display and to confer prestige, it is certain that such charts—probably simple, unadorned ones—were used on ships, although the details of their on-board usage are not entirely clear.[3] While the *mappaemundi* of the clerical intellectual elite of the day provided a qualitative description of the world, based on a mental image only, portolan charts are geometrically correct within certain accuracy limits and are therefore clearly based on measurements. They are the first maps to be drawn to scale since Claudius Ptolemy's maps, and they usually contain several scale bars. It is striking that they emerged in the milieu of maritime commerce, apparently with no or limited involvement on the part of the intellectual clergy.

The charts contain no graticule of parallels and meridians but, rather, display a criss-cross pattern of straight lines, which were drawn by interconnecting sixteen regularly distributed points on a (hidden) circle (see Figure 1). This pattern is known as a wind rose, and its lines indicate thirty-two (not sixteen!) regularly spaced directions or bearings, which survived into modern times as the thirty-two "points" of the compass.

The oldest charts are usually equipped with two wind roses, covering the eastern and western half of the chart, respectively. From the middle of the fourteenth century more and more charts were produced with a single wind rose. The lines are presumed to have been used for navigation purposes, to read the course bearing of a route planned on the chart. The lines are color-coded in black, red, and green to facilitate identification of the correct bearing. The map image (i.e., the coastlines) is rotated by about 9 degrees counterclockwise with respect to the wind rose. This rotation is commonly attributed to the average magnetic declination in the medieval Mediterranean and thus is widely seen as proof that these maps are based on magnetic compass measurements made by medieval sailors. Magnetic course bearings express

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[2] Roel Nicolai, *A Critical Review of the Hypothesis of a Medieval Origin for Portolan Charts* (Ph.D. diss., Univ. Utrecht, 2014) (Houten: Educatieve Media, 2014). A revised version will be published as Nicolai, *The Enigma of the Origin of Portolan Charts: A Geodetic Analysis of the Hypothesis of a Medieval Origin* (Leiden: Brill), in early 2016. The present article renders the complex argument unfolded in the book in a more compact and accessible fashion and also presents some additional material.

[3] Regarding the certainty that portolan charts were used on ships see Ramon J. Pujades i Bataller, *Les cartes portolanes: La representatició medieval d'una mar solcada*, trans. Richard Rees (Barcelona: Lunwerg, 2007), p. 439.

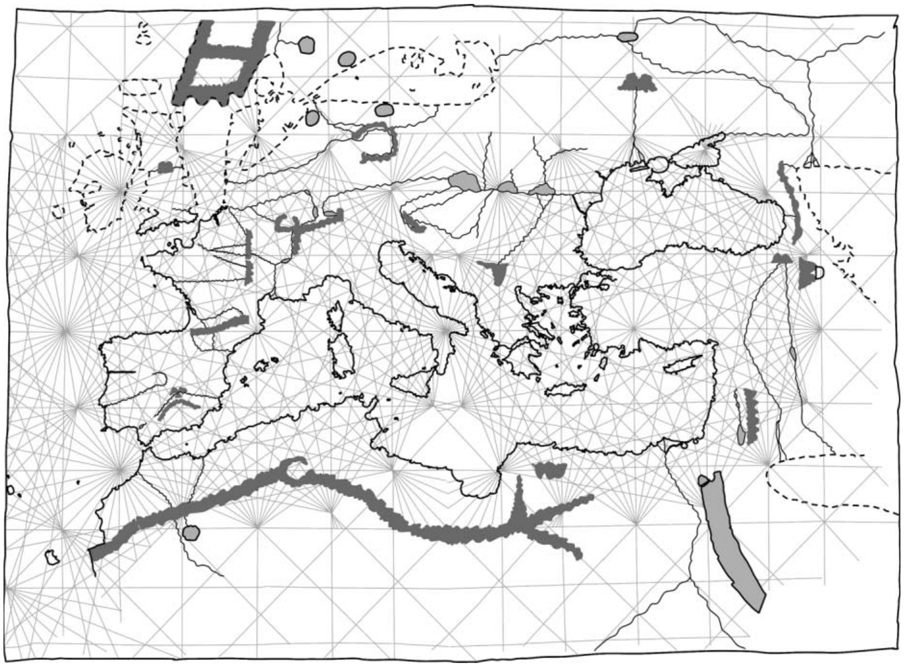

Figure 1. Tracing of the portolan chart by Angelino Dulcert (1339). The dimensions of the original chart, located at the Bibliothèque nationale de France, Paris, are approximately 75 cm x 105 cm. Unlike most portolan charts, this chart consists of two sheets of vellum stuck together. The dashed coastlines indicate the area outside the accurate core area of the chart. The two wind roses are shown in grey so as not to obscure the coastline details.

the course direction relative to magnetic north, not true (geographic) north. The difference between true north and magnetic north is the magnetic declination; a positive value for magnetic declination means that a magnetic needle would point east of true north. Magnetic declination as a phenomenon was unknown in the medieval Mediterranean world.

The coastlines of the accurate core area of Mediterranean portolan charts were to a large extent copied from earlier portolan charts. That does not imply that the extant charts are "slavish" copies of a single original, as was suggested by Adolf Erik Nordenskiöld, but the similarities in the coastline shape are far more noticeable than the differences. Research has uncovered other interesting aspects of the geometric characteristics of these charts. In 1987 Scott Loomer established the Mercator projection as the best-fitting map projection from a list of nine candidate projections, with the equirectangular projection a close runner-up.[4] Furthermore, regional scale differences exist in various parts of every portolan chart. This has been known since the middle of the nineteenth century and is usually interpreted as an indication that portolan charts are mosaics of partial charts of independently charted subbasins of the Mediterranean.

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[4] Adolf E. Nordenskiöld, *Periplus: An Essay on the Early History of Charts and Sailing-Directions*, trans. Francis A. Bather (Stockholm: P. A. Norstedt, 1897), facsimile rpt. (Eastford, Conn.: Marino, 2003), p. 18; and Scott A. Loomer, "A Cartometric Analysis of Portolan Charts: A Search for Methodology" (Ph.D. diss., Univ. Wisconsin–Madison, 1987), pp. 133, 146.

A curious characteristic of portolan charts is the fact that while they are very realistic with respect to the entire Mediterranean and Black Sea area, in many places the local coastal *detail* is poor.[5] This is paradoxical, given that these charts are supposed to have been built up from surface measurements: such a construction process would work from the details toward the whole. To achieve a certain degree of accuracy for the entire chart, the details have to be mapped with *greater* accuracy, as errors will, on statistical grounds, not automatically cancel out but instead accumulate as the area being mapped is extended. In addition to the poor agreement with reality along local stretches of coastline that we see on surviving portolan charts, numerous coastal features have also been exaggerated in size: bays are deeper than they would be when drawn to scale, while promontories tend to be larger.

THE CONSENSUS VIEW: A MEDIEVAL EUROPEAN ORIGIN

The hypothesis of a medieval origin for portolan charts describes what has been understood as the most likely scenario. I would stress again that the medieval origin of the surviving *physical* charts is not disputed. My challenge concerns the origin of the accurate rendering of the overall coastline geometry. Although there are still a few proponents of an ancient origin, the charts themselves do not contain even a hint of such an origin. They show no similarity to the maps of Claudius Ptolemy.[6] Researchers who propose an ancient origin usually do so because they reject a medieval European origin as inadequate to explain the accuracy of the charts. An Arabic-Islamic origin is highly improbable, as the earliest extant Arabic-Islamic charts date from the fifteenth century and quantitative analysis has shown that they are less accurate than European portolan charts, of which they appear to be copies.[7] By a process of elimination, therefore, scholars arrive at a hypothesis of a medieval European origin, with the most likely site the Ligurian coast of Italy.

The associated question of *how* these charts were constructed is far more difficult to answer, and many researchers who study portolan charts hold the view that, while they feel certain of the charts' medieval origin, the process of their construction is not (yet) well enough understood. I noted earlier that a presumed medieval origin of the charts requires an explanation of how they are supposed to have been constructed that can be reconciled with what is known about the state of medieval science and technology. While specific details are avoided in many published variants of the hypothesis of a medieval origin, the most likely account of the hypothesized process of construction runs as follows.[8]

1. It is assumed that medieval European mariners practiced a disciplined form of navigation, estimating the speed and direction of the ship at regular intervals—for example, four-hour watch intervals. The navigation technique in which one starts at a known location and calculates the change in position from speed and bearing is known as *dead reckoning.* Estimated or measured values of successive intervals are

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[5] Nicolai, *Critical Review of the Hypothesis of a Medieval Origin for Portolan Charts* (cit. n. 2), pp. 36–37. See Section 2.2.2: "A Contradiction of Tobler's First Law of Geography" for a more extensive description. See also Patrick Gautier Dalché, "Cartes marines, représentation du littoral et perception de l'espace au Moyen Âge: Un état de la question," in *Castrum VII: Zones côtières et plaines littorales dans le monde méditerranéen au Moyen* Age, ed. Jean-Marie Martin (Rome: École Française de Rome, 2002), pp. 25–28.

[6] Pujades, *Les cartes portolanes* (cit. n. 3), pp. 506–508.

[7] Loomer, "Cartometric Analysis of Portolan Charts" (cit. n. 4), p. 148; and Pujades, *Les cartes portolanes*, pp. 508–509.

[8] The four points listed paraphrase and elaborate the account in Tony Campbell, "Portolan Charts from the Late Thirteenth Century to 1500," in *The History of Cartography*, Vol. 1: *Cartography in Prehistoric, Ancient, and Medieval Europe and the Mediterranean*, ed. J. B. Harley and David Woodward (Chicago: Univ. Chicago Press, 1987), pp. 371–463, esp. p. 388.

assumed to have been compounded into a single bearing and distance for a journey between any two coastal points along the route the ship traveled. Data of this sort is presumed to form the empirical basis of the portolan chart. The magnetic compass emerged practically simultaneously with portolan charts in the Mediterranean, and it is therefore still a subject of debate among proponents of a medieval origin whether or not the compass was used in portolan chart construction.

2. The estimates of bearings and distances between coastal points from many journeys and many mariners are presumed to have been collated centrally, thus forming a body of quantitative geometric data of the Mediterranean, the Black Sea, and the Atlantic coasts. A process of improvement in the accuracy of the quantitative knowledge of directions and distances between coastal points is generally assumed. This assumption is justified by the intuitive notion that a single measurement of any distance or bearing would be insufficiently precise to explain the accuracy of portolan charts. Some authors speak of "averaging," but the majority do not specify any process through which the accuracy of these estimates might have been improved.[9]
3. The first portolan chart is presumed to have been constructed from this conjectural centrally collated body of navigation data using a technique known as *plane charting*. Plane charting assumes a flat or plane geometry for the surface of the earth: in other words, the curvature of the earth's surface is ignored. It was widely believed in the Middle Ages that the earth is indeed spherical, but it was not understood how one should account for the curvature of its surface in the construction of maps. Modern researchers who study portolan charts generally agree that any data mismatches that would have arisen from measurement errors were corrected, or "reconciled," by some empirical graphical method, while the effects of earth curvature on charting are considered to be negligible. The assumption that no geodetic-cartographic map projection was used in their construction is usually expressed by assertions that portolan charts are *projectionless*.[10]
4. These assertions seem to be contradicted by the results of research using methods of *cartometric analysis*. Cartometric analysis is any form of numerical analysis of the geometric properties of a map or chart. Such methods have demonstrated that the map image of portolan charts shows remarkably good agreement with the map image of a modern map based on the Mercator projection. In spite of these results, broad consensus exists among portolan chart researchers that there is no contradiction at all. They consider the close agreement with any map projection to be an *unintentional by-product* of the plane-charting technique. This view is put forth without any supporting evidence and is often justified only by statements to the effect that the "effects of earth curvature are negligible in a relatively small portion of the earth's surface such as the Mediterranean."[11] This assumption is mandatory in order to uphold the hypothesis of a medieval origin of portolan charts constructed from measured distances and bearings: medieval cartographers would not have known how

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[9] See, e.g., Pujades, *Les cartes portolanes* (cit. n. 3), p. 510; and Heinrich Winter, "The Origin of the Sea Chart," *Imago Mundi*, 1956, *13*:39–44, esp. p. 39.

[10] Campbell, "Portolan Charts from the Late Thirteenth Century to 1500" (cit. n. 8), p. 385; and Armando Cortesão, *History of Portuguese Cartography*, Vol. 1 (Coimbra: Junta de Investigações de Ultramar-Lisboa, 1969), p. 217.

[11] Cortesão, *History of Portuguese Cartography*, Vol. 1, p. 365; and Eva R. Taylor, "The Sailor in the Middle Ages," *Journal of Navigation*, 1948, *1*:191–196, on p. 191 (quotation). See also Richard Pflederer, "Portolan Charts—Vital Tool of the Age of Discovery, Sailing Guides," *History Today*, 2002, 52(5), http://www.historytoday.com/richard-pflederer/portolan-charts.

> to correct the raw measurements in such a way that a Mercator or similar projection would emerge. This knowledge only developed centuries later.

For the hypothesis of a medieval origin to be accepted as true, all four of these assumptions must hold: they build on one another, culminating in assumption 4. In spite of the consensus, there is also broad agreement among researchers that the hypothesis of a medieval origin is not corroborated by any evidence. Tony Campbell makes the point in tactful but clear terms in his 1987 contribution to the *History of Cartography* project: "Among the research problems connected with portolan charts, the question of their origin is perhaps the most intractable. . . . Despite the thousands of scholarly words expended on the subject, most of the hypotheses about portolan chart origins have remained just that. In the absence of corroborating data they often appear to be less explanations than creation myths." Patrick Gautier Dalché expresses the same view more bluntly: "The question of the origins of these charts has given rise to a torrent of theories, of which the essential characteristic is that none of them has a solid foundation." Ramon Pujades i Bataller summarized the situation as follows: "[Because the charts are] often examined only from the geographical perspective and on the fringe of any kind of historical contextualization[,] an extremely wide variety of opinions—often more dogmatic than scientific—have been expressed regarding the time and place of their birth."[12]

Not every researcher will subscribe to the four-point hypothesis outlined above. A recent trend is to avoid being specific about the charts' origin and construction method, seeing them as "the offspring, not of a specific place, but of a Mediterranean seaborne culture in its broadest geographical sense—a heritage as common as the *lingua franca*, or mixture of languages, that seamen used," as Pujades describes this trend.[13] Gautier Dalché sees portolan charts as the product of "Mediterranean maritime culture in its entirety, characterized by multiple cultural exchanges." According to him, portolan charts are an expression of a "revolution in the representation of space."[14] The close agreement of portolan charts with the Mercator map projection is dismissed as irrelevant or as an optical illusion or is not even mentioned, and the accuracy of the charts is played down.[15] The apparently deliberate lack of specificity of such "explanations" makes verification or falsification next to impossible.

We might ask whether the hypothesis of a medieval origin for portolan charts lends itself to scientific verification (or falsification) at all or whether the answers are forever lost "in the mists of time." Indeed, considerably more numerical information may be extracted from these charts than has been obtained until now, and such information may facilitate proper testing of the hypothesis of a medieval origin. The history of cartography is usually considered to belong to the domain of the humanities. Although there have been excursions into more exact, numerical methods of analysis, portolan charts and their hypothesized construction process have never been approached from the perspective of *geodesy*. While the domain of cartography may be described as the representation of spatial information in the form of maps, geodesy comprises not only the study of the size

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[12] Campbell, "Portolan Charts from the Late Thirteenth Century to 1500" (cit. n. 8), p. 380; Patrick Gautier Dalché, *Carte marine et portolan au XIIe siècle: Le "Liber de existencia rivierarum et forma maris nostri mediterranei" (Pise, circe 1200)* (Rome: École Française de Rome, 1995), p. 28; and Pujades, *Les cartes portolanes* (cit. n. 3), p. 506.

[13] Pujades, *Les cartes portolanes*, p. 515. Pujades does not support this notion.

[14] Gautier Dalché, "Cartes marines, représentation du littoral et perception de l'espace au Moyen Âge" (cit. n. 5), pp. 20, 31.

[15] *Ibid.*, pp. 15, 25–28; and Pujades, *Les cartes portolanes* (cit. n. 3), p. 460.

and shape of the earth but, applied to smaller parts of the earth's surface, also the establishment of geodetic frameworks that form the geometric basis of modern maps and charts. Such geodetic (or geometric) frameworks are built up from surface—and, nowadays, surface-to-space—geodetic measurements. Examples are found in the classical triangulation networks that underlie the national mapping of most countries. A more pertinent example would be the centrally collated body of distances and bearings, referred to earlier, that would collectively build up such a geometric framework covering the Mediterranean and the Black Sea. It is from such a network of bearings and distances between coastal points such as ports and landmarks that portolan charts are presumed to have been drawn. The question of how accurate the underlying measurements need to be to produce a map of a prespecified accuracy is a fundamentally geodetic question, as is the question of whether the Mercator or any other projection might emerge coincidentally from the "plane-charting" process.

This essay focuses on the compatibility of the Mercator projection, or a similar map projection, with the image of the coastlines on a portolan chart produced by plane charting. It will be shown that such a projection is incompatible with that simple construction method and that therefore the whole hypothesis of a medieval origin will have to be rejected.

THE ACCURACY OF PORTOLAN CHARTS

Before immersing the reader in the question of the map projection, I must establish the accuracy of portolan charts. This, in turn, introduces the question of how the concept of the "accuracy" of a map or chart is to be defined. The accuracy of a measurement is usually defined as the closeness of that value to its true value. One might therefore be tempted to expand this principle to a map: measure distances and angles between a number of representative points on the map and compare them with the true values between these points in the "real world," after correction for the scale of the map. This approach would, however, fail to take into account that the "true" values are measured on the spherical earth, whereas the measurements on the map are made on a flat surface. In other words, this comparative measurement would fail to take into account the inevitable distortions that result from projecting spherical geometry onto a flat surface. That such projection is not possible without distorting the spherical surface is readily demonstrated when one tries to flatten a large piece of orange peel: it cannot be done without stretching or tearing the peel. Before map accuracy can be estimated in the way outlined above, it must be known how the distances and angles measured on the map are distorted by the map projection. Each type of map projection introduces its own characteristic distortions of angles and distances between points. For example, parallels and meridians are shown as straight lines on some map projections and as curved lines on others. Moreover, their spacing may vary. Thus each map projection has its own characteristic "fingerprint" of distortions. The distortion of distances may be calculated for many map projections as a multiplication or scale factor. Only when that scale distortion has been taken into account can distances between points on the map be compared with corresponding distances on the earth's surface and the difference between the two used to quantify errors in the mapping of geographic features—in other words, to establish the accuracy of the map or chart.

The Mercator projection is a *conformal* map projection—that is, it renders small shapes without distortion. Furthermore, it projects a *rhumb line*, a line that intersects all meridians at a constant angle on the sphere, as a straight line on the map. It is this property that makes the Mercator projection so exceptionally useful in navigation, because the course of a ship that keeps a constant compass bearing is a rhumb line on the sphere. The ship's course therefore plots as a straight line on a Mercator chart. The Mercator projection does come with

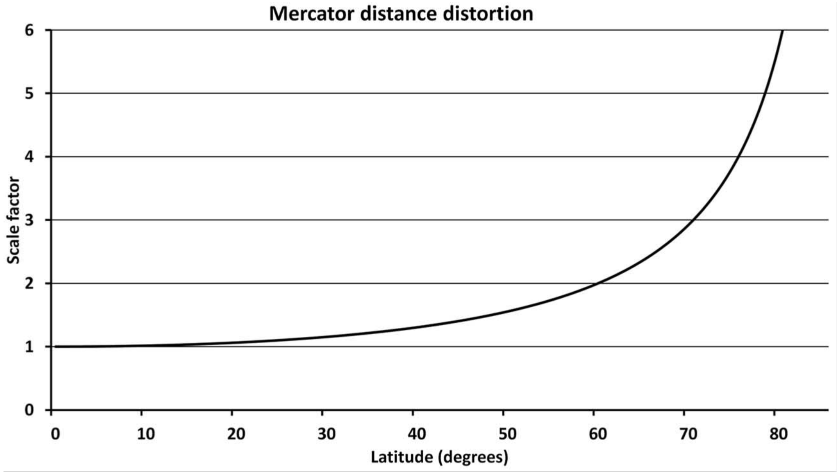

Figure 2. Scale distortion of distances in the Mercator projection.

a drawback: its scale becomes progressively larger as latitude increases (see Figure 2). In order to plot the change in a ship's position after a day's sailing on a Mercator chart correctly using dead reckoning, a navigator must stretch the distance sailed by the ship during the day accordingly. The length of a segment of rhumb line on the sphere is shorter than its corresponding length on the Mercator chart by a factor approximately equal to the cosine of the average latitude of that line segment, after the nominal scale of the chart has been taken into consideration.

When it is known or suspected that a portolan chart is based on the Mercator projection or closely resembles such a projection (or any other projection, for that matter), a researcher may digitally determine a "best fit" between the portolan chart and a reference Mercator map by shifting the portolan chart, rotating it and changing its scale until a "best fit" with the reference chart is achieved. This may be done computationally by executing this "best-fitting" process using a least-squares algorithm. In this process a large number of corresponding pairs of points on the portolan chart and the reference chart, called *identical points*, are selected; then the best-fitting process is executed on those points. The two charts will of course not be a perfect match; small differences, called *residuals* or *residual errors*, will remain in the positions of identical points on the portolan chart after the best fit to the reference map. The least-squares algorithm minimizes the sum of the squares of these residuals by optimizing the shift, rotation, and scale of the portolan chart with respect to the reference chart. When all systematic distortion components have thus been removed in the best-fitting process, the residual errors in X and Y coordinates of the chart will reflect the *random errors* in the identical points and are representative of the accuracy of the chart. The Mean Squared Error (MSE) needs to be computed separately for the X coordinates and the Y coordinates, and the larger of the two is taken as a measure of the *accuracy of the chart* ($\mathrm{MSE}_{\mathrm{chart}}$). That is usually a somewhat conservative estimate of map accuracy, as it ignores the fact that the map may be more accurate in the complementary direction.[16] It is customary to express chart accuracy as

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[16] This may be illustrated by a simple example. If the MSE value in the X direction of the map and the MSE in the Y direction of the map were both 100 km^2, the map may be said to have a map accuracy of 10 km in all directions. Had the squares of

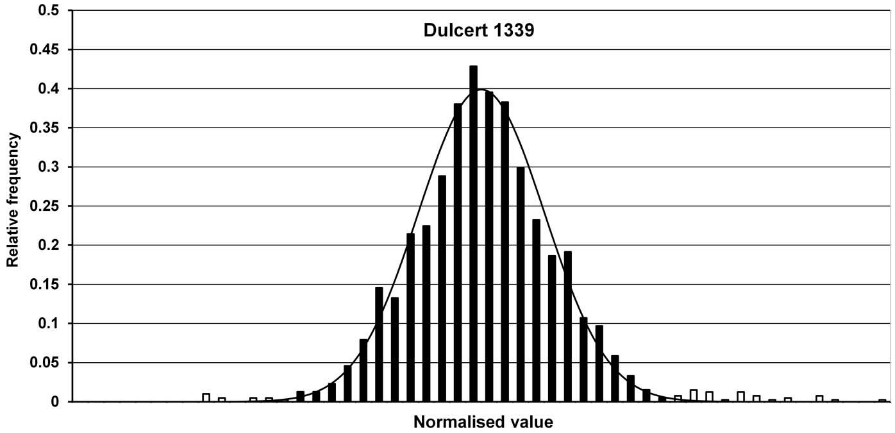

Figure 3. Histogram of the (normalized) residuals in the 836 identical points of the portolan chart of Angelino Dulcert (1339) after application of a piecewise best-fitting process to the Mercator projection. The solid black line is the theoretical normal or Gaussian error distribution. The white bars in the tails of the distributions belong to identical points that were rejected in the least-squares fit.

a linear quantity and take the square root of that number, the Root Mean Squared Error, or $\text{RMSE}_{\text{chart}}$, which may be interpreted as the *mean point accuracy* of the map or chart. The concept of *chart accuracy* assumes randomness of the remaining map errors, which will exhibit a certain spread around a mean value of zero (see Figure 3).

If the underlying map projection of portolan charts is not the Mercator projection but another type of projection— or perhaps no projection at all—the mean of all residuals will not be close to zero but will deviate systematically from zero, and the distribution of the residuals will be skewed. The MSE will in that case be larger, as it will contain not only the contribution of the random chart errors but, in addition, a systematic component or bias, consisting of the sum of the squares of all systematic deviations in the identical points. One may use this principle to determine what the best-fitting map projection to a portolan chart is. Map projections that do not fit as well as others will have a larger MSE because of this bias. After all, the accuracy of the chart remains the same; only the systematic deviation or bias in the MSE changes, depending on whether the map projection used in the cartometric analysis is a better or worse approximation of the true map projection of the chart.

This approach was followed by Loomer, who found that the Mercator projection resulted in the smallest MSE for all twenty-six portolan charts he investigated. This does not prove that portolan charts are based on the Mercator projection, however. Another projection may fit better yet; or, as the consensus view on this matter holds, there may not be an underlying projection even though it may look like it—in much the way that one may sometimes seem to see a human face that is not really there in the knots and depressions of a tree trunk.

My analysis of five early portolan charts distinguished itself from most other cartometric studies in that I treated each chart as a composite of several partial charts instead of as a single

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the residuals in the X and the Y directions been added together, the sum would have amounted to 200 km^2. The square root of that figure would be about 14 km, which would be an incorrect value for the accuracy of the map. For that reason the residuals in the X coordinates and the residuals in the Y coordinates need to be separated.

Table 1. Five Portolan Charts Analyzed

Name in This Article	Cartographer	Date of Creation	Location	Catalogue Number	Identical Points
Carte Pisane	Anon. Genoese	End 13th century	BnF, Cartes et Plans, Paris	Ge B 1118	444
Ricc 3827	Anon. Genoese	1300–1325	Bib. Riccardiana, Florence	3827	1,015
Dulcert 1339	Angelino Dulcert	1339	BnF, Cartes et Plans, Paris	Ge B 696	836
Ristow- Skelton No. 3 (RS-3)	Anon. Genoese	1325–1350	Library of Congress, Washington		742
Roselli 1466	Petrus Roselli	1466	James Ford Bell Library, Minneapolis	bell001281466 mRo	860

Source.—Roel Nicolai, *A Critical Review of the Hypothesis of a Medieval Origin for Portolan Charts* (Ph.D. diss., Univ. Utrecht, 2014) (Houten: Educatieve Media, 2014), Ch. 7: “Cartometric Analysis of Five Charts.”

entity. (See Table 1.) If portolan charts are indeed mosaic charts, as all relevant research seems to indicate, then it is incorrect to analyze them as single coherent entities.[17] I did not make *a priori* assumptions about the exact extents of the subcharts and the locations of their joins but determined these iteratively from the data by means of statistical testing. The rejection of one identical point at a time will *reduce* the MSE of the remaining subset of points if the rejected point is inconsistent with that subset. This procedure, which is entirely repeatable, allows for the establishment of a number of coherent subsets of points, which may be interpreted to correspond to subcharts, each with its own scale and orientation. The differences in scale and orientation per subchart that were thus computed were statistically significant. Almost as a by-product, the *chart accuracy* was determined per subchart of each of the five portolan charts analyzed (see Figure 4).

An $\mathrm{RMSE}_{\mathrm{chart}}$ of 11 km corresponds to about 2 mm on the chart, which is extremely accurate for a medieval chart, even when one realizes that the RMSE indicates the radius of a circle of uncertainty corresponding with a confidence level of approximately 39 percent. This is much better than has been assumed until now—which is understandable, since all researchers who have conducted quantitative analyses of portolan charts treated them as single entities, not as composites of subcharts.

Analysis of the five charts confirms that portolan charts are mosaic charts (see Figure 5). There is significant agreement in the locations of the joins between the subcharts across the portolan charts analyzed, although some important differences have come to light as well.

The most important and intriguing aspect of these subcharts is that their boundaries or joins do not follow the expected boundaries of the traditional sub-basins of the Mediterranean

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[17] On portolan charts as mosaics see, e.g., Loomer, “Cartometric Analysis of Portolan Charts” (cit. n. 4), pp. 160–165.

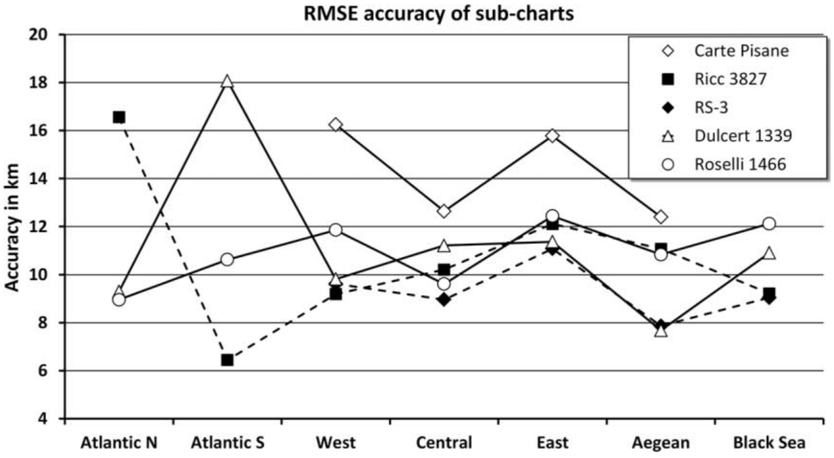

Figure 4. Accuracy (RMSE) of the subcharts of a Mediterranean portolan chart.

(e.g., Aegean Sea, Adriatic Sea, etc.), as is usually assumed. The subcharts that constitute the mosaic chart of the Mediterranean notably exhibit considerable overlaps and some gaps, as shown in Figure 5. In view of the ultimate conclusion that these charts cannot be medieval, the overlaps of the subcharts suggest that the mosaic was composed by overlaying common sections of coastlines on the original partial charts. This process may explain why the scales and orientations of adjacent subcharts are similar in magnitude, as shown in Figures 6 and 7. Joining two adjacent subcharts in this manner may be done using different sections of

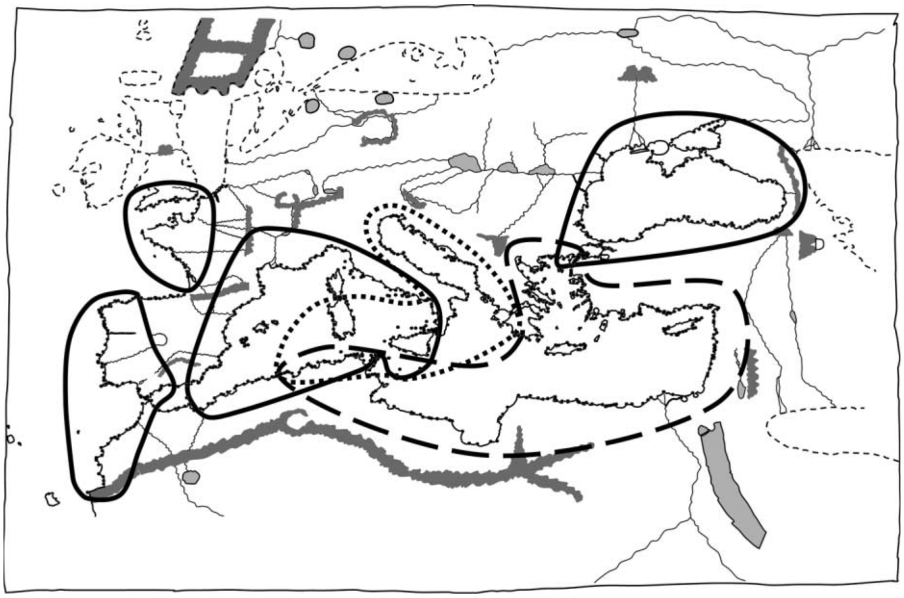

Figure 5. Tracing of the portolan chart by Angelino Dulcert (1339) with 836 identical points, divided into coherent subsets of points, identified with partial charts.

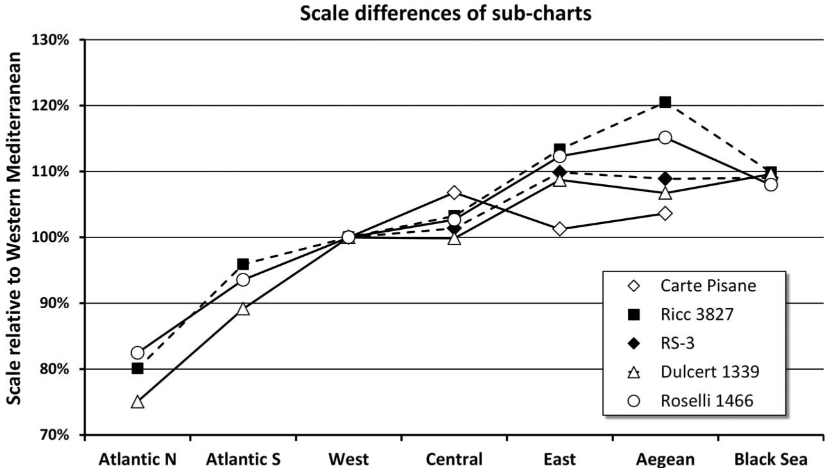

Figure 6. Scale differences per subchart, relative to the scale of the Western Mediterranean.

common coastline, which may explain the geometric differences between various portolan charts covering the entire Mediterranean, the Black Sea, and the Atlantic coast. It appears that medieval cartographers made trial-and-error attempts to create a more realistic mosaic chart, possibly based on feedback from sailors. A famous example that is usually cited is Francesco Beccari's portolan chart of 1403, on which the author notes that he adjusted the locations of Sardinia and Corsica and increased the scale of the Atlantic coast, shown on the chart, on the basis of feedback he received from mariners. Beccari was not the only one who made

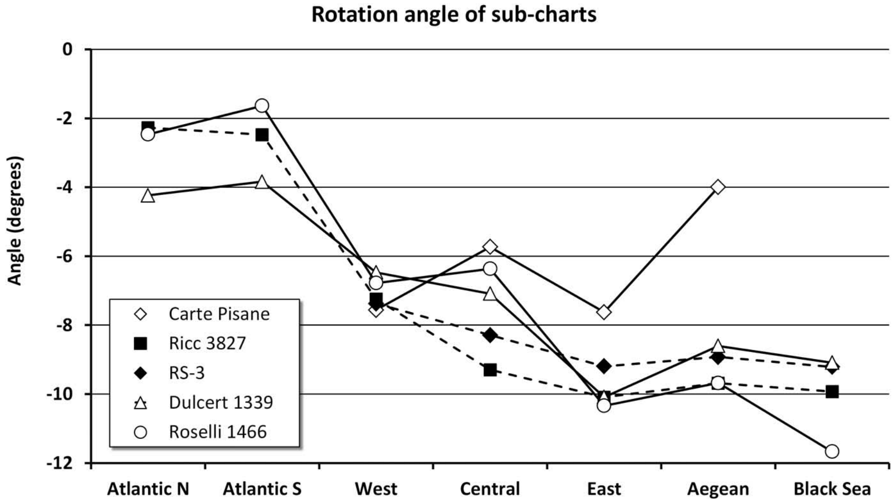

Figure 7. Rotation angles of subcharts with respect to the wind rose(s) on each chart.

modifications to the design of his portolan charts; nor was he the first, as a comparison of the locations of Corsica and Sardinia on the five charts I analyzed demonstrates.[18]

PLANE CHARTING AND THE CONSTRUCTION OF A MERCATOR CHART

The process of constructing a chart using the Mercator projection from geometric measurements made aboard ships has the following in common with the process of dead-reckoning navigation using a Mercator chart. In both cases measurements of sailed distance and course direction are used, in the first case to plot the position of coastal features on the map and in the second to plot the ship's position. In both cases, as well, these measurements require a correction to account for the different geometrical characteristics of the spherical surface of the earth and the plane surface of the chart. As explained earlier, the Mercator projection does not require the course direction to be corrected, but distance sailed must be corrected by dividing it by the cosine of the mean latitude.[19] After correction for nominal chart scale, distances on a Mercator chart are therefore in principle longer than corresponding distances on the spherical earth, as the cosine of latitude varies from unity at the equator to zero at the poles.[20]

In the process of plane charting no corrections are made to any geometrical measurement made on the surface of the spherical earth. For the course bearing that is likewise true for Mercator charting, but with regard to the distances the two methods diverge considerably. Take two equal distances on the sphere in the Western Mediterranean, one along the northern coast and one along the southern Mahgreb coast: the distance along the northern coast would project some 10 percent longer on a Mercator chart than the distance along the southern coast.

The plane-charting process that is described as part of the four-point origin hypothesis implies that all data mismatches, whether they result from measurement errors or from ignoring earth curvature—the two error sources are indistinguishable—were reconciled by some graphical method. It is impossible to reconstruct such a method reliably, as there are an unlimited number of ways in which that might be done, but a guiding principle may be established as follows. The hypothetical medieval cartographer, in the process of drawing his chart from the presumed centrally available body of navigation data, would discover a data conflict when the position of the same point—for example, a cape— could be determined by two bearing and distance pairs from different points that have already been charted, as shown in Figure 8. The most likely way he would have dealt with such conflicting information would be to draw the cape somewhere in the middle, between the two independent position determinations. The same would hold if more bearings and distances to the same cape were available. This principle can easily be simulated in the least-squares calculation process by allocating appropriate weights to the different bearings and distances in the assumed geodetic network.

For the plane-charting process to produce, by coincidence, an image compatible with the

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[18] Nicolai, *Critical Review of the Hypothesis of a Medieval Origin for Portolan Charts* (cit. n. 2), pp. 243–245 (Section 7.6.4: "The Wanderings of Corsica and Sardinia").

[19] This is an approximation, as the latitude of the ship changes as it sails any course different from due east or due west.

[20] In nautical practice the situation is slightly more complex, as nautical charts on the Mercator projection have been designed to be true to scale at a specified parallel of latitude. Distances on the chart are longer than those on the sphere when they are situated at a higher latitude than the true-to-scale parallel and shorter when situated at a lower latitude.

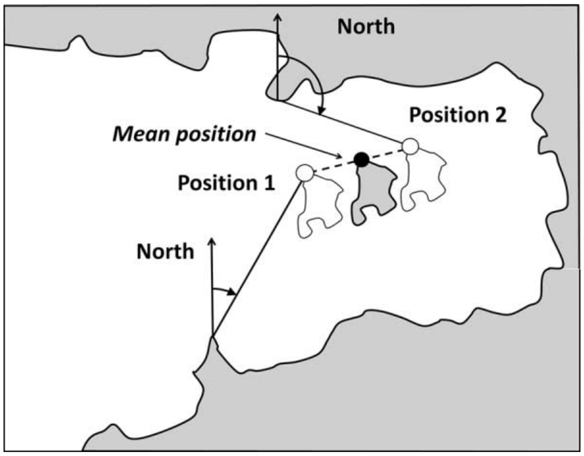

Figure 8. Position reconciliation principle adopted in the geodetic analysis of plane charting.

Mercator projection, the following conditions need to be satisfied. The combination of measurement errors and the corrections made to the distances in the graphic reconciliation process, as illustrated in Figure 8, *should coincidentally produce the pattern of latitude-dependent scale corrections of the Mercator projection*.

But directional data is also affected. The spatial variation of magnetic declination in the Mediterranean area, calculated for the year 1250, is shown in Figure 9. However, no trace of the spatial variation in magnetic declination is visible in the chart residuals after the least-squares fit to the Mercator projection (see Figure 3), as this would have introduced skewing of the distribution of residuals. Therefore, with regard to the bearings between coastal features, the combination of measurement errors and corrections applied in the graphic reconciliation process *should coincidentally produce a pattern that reflects the spatial variation in magnetic declination to eliminate its effects on charting*.

The probability of such a complex pattern of measurement errors and plane-charting corrections occurring accidentally in a large dataset is negligibly small, especially given that this should have happened everywhere in the core coverage area of the portolan chart, from the Atlantic coast to the Black Sea.

It is therefore unlikely, if not impossible, that the Mercator projection or a similar projection would ever emerge accidentally from a medieval dataset of distances and bearings and from a hypothetical graphic plane-charting process; nonetheless, experimental verification of this theoretical analysis is desirable.

IS THE MAP PROJECTION OF A PORTOLAN CHART COINCIDENTAL?

The best if not the only way to verify the conclusion drawn on theoretical grounds, described in the last paragraph of the previous section, is to simulate the putative medieval plane-charting process and compare the resulting shape of the coastlines with their shape on the Mercator projection. This process consists of the following steps.

1. The input to the process will not be a real dataset of distances and bearings measured on medieval ships in accordance with what we presume to be the medieval manner of navigation but, rather, a set of bearings and distances

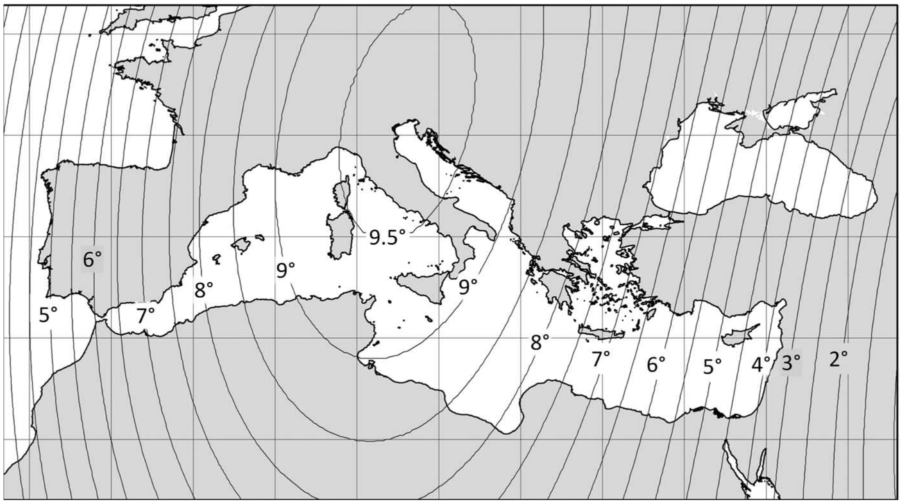

Figure 9. Magnetic declination for the year 1250, calculated from the paleomagnetic model CALS7k.2. The values shown are positive, which means that a compass needle would have pointed away from north, toward the east, by the amounts shown on this map. See M. Korte, A. Genevey, C. G. Constable, U. Frank, and E. Schnepp, "Continuous Geomagnetic Field Models for the Past Seven Millennia, I: A New Global Data Compilation," *Geochemistry, Geophysics, Geosystems*, 2005, 6(20):1–28, Q02H16, doi:10.1029/2004GC000800; and Korte and Constable, "Continuous Geomagnetic Field Models for the Past Seven Millennia, II: CALS7K," *ibid.*, pp. 1–18, Q02H16, doi:10.1029/2004GC000801.

calculated between points along the Mediterranean coastline that have been scaled from a modern map. The errors in those positions are negligible in comparison with those found on a portolan chart, and they may therefore be considered to be error free. Hence also the values of the bearings and distances calculated from those positions may be considered to be error free. These bearings and distances will be calculated over a spherical earth of modern dimensions. The outcome of this step is a geodetic network or framework of error-free distances and bearings on the curved surface of the earth, computed between the selected coastal points that constitute the nodes of the framework. To simulate medieval compass bearings, the calculated bearings will have the magnetic declination for the year 1250 applied to them.

2. When the network of distances and bearings between coastal points is flattened in the plane mismatches will appear owing to the fact that earth curvature is ignored. The hypothesis of a medieval origin for portolan charts assumes that the cartographer managed to reconcile these data mismatches (which the hypothesis considers to be negligible), together with data mismatches due to measurement errors, by some graphical adjustment process. I have simulated this presumed process by performing the adjustment using least-squares estimation (LSE) with measurement weights mimicking the process illustrated in Figure 8. LSE will compute corrections to the bearings and distances such that they will fit together in the map plane, as well as calculating the optimum positions of the coastal points described in step 1. This will warp the shape of the geodetic framework and, hence, the coastline shape that would

result from "joining the dots" of the geodetic framework nodes. Let the coastline shape thus constructed be referred to as a *synthetic portolan chart*. The question is whether this warping of the coastline shape is enough to be have a measurable impact. No measurement errors play a role in the generation of this synthetic portolan chart, only magnetic declination and the effects of ignoring earth curvature.

3. If the map projection is indeed a coincidental by-product of the plane-charting process, the warped shape of the coastlines—that is, the synthetic portolan chart—will agree closely with the coastline shape found on a real portolan chart. This can be measured by subjecting the synthetic portolan chart to the same process of cartometric analysis to which the real charts were subjected.

A realistic geodetic framework of distances and compass bearings needs to be specified, one that takes properly into account the trade routes and prevailing summer winds in the Mediterranean and the Black Sea. A key factor that determined the preference for certain routes and the avoidance of others was the consistency of the summer winds in the Mediterranean. The dominant wind direction is north to northwest. Thus for most of the summer the southern shores were lee shores, which any sailor would rather avoid—and certainly with a sailing ship that had difficulty in making headway against the wind. Moreover, the many reefs and rocky shoals along the southern shores increased the danger of running aground. There are few islands along the southern coast that might offer shelter in case of sudden adverse weather. The northern shores are safer. Many islands, surrounded by deep water, offered shelter in an emergency, and on them, in contrast to the islands on the southern coast, fresh water was readily available. All these factors led to the development of a maritime trunk route that ran along the northern Mediterranean coast.[21] Some writers have claimed that, thanks to its lateen rig, a medieval ship could sail any course its master wished except due into the wind, but this is an unduly optimistic and naive view. The advantage offered by this type of rig, if such an advantage existed, was largely undone by the rounded bilges of the hull, which offered little or no resistance to leeway.[22]

Sailing routes over open sea would therefore have been mainly in a southern to southeastern direction. Christian sailors certainly frequented Moslem trading ports in North Africa, but the bulk of the shipping to and from Byzantium and the Levant followed the northern coast. Routes along the southern coast would also have been used, but far less frequently than the trunk route along the northern coast.

With these considerations in mind, I constructed three geodetic networks, for the Western and Eastern Mediterranean and for the Black Sea (see Figure 10). Following steps 1 and 2 of the process described above, positions of the nodal points along the coast and islands may be calculated by means of least-squares estimation. These positions, representing the synthetic portolan chart, were then fed into the same cartometric analysis process as the identical points selected on the real portolan charts, as described in step 3. The Mean Squared Error of the fit to the Mercator projection, $\mathrm{MSE}_{\text{plane charting}}$, is a measure of the mismatch in shape between the synthetic chart—in essence, the plane-charted network that was computed—and the Mercator projection. If the Mercator projection is a coincidental by-product of the plane-

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[21] John H. Pryor, *Geography, Technology, and War: Studies in the Maritime History of the Mediterranean, 649–1571*, paperback ed. (Cambridge: Cambridge Univ. Press, 1992), pp. 21, 53.

[22] For the suggestion that lateen rigs offered significant choice in the matter of sailing course see David W. Waters, *The Art of Navigation in England in Elizabethan and Early Stuart Times* (London: Hollis & Carter, 1958), p. 21. For the view that the rounded bilges of the hull would counteract those advantages see Pryor, *Geography, Technology, and War*, pp. 34–37.

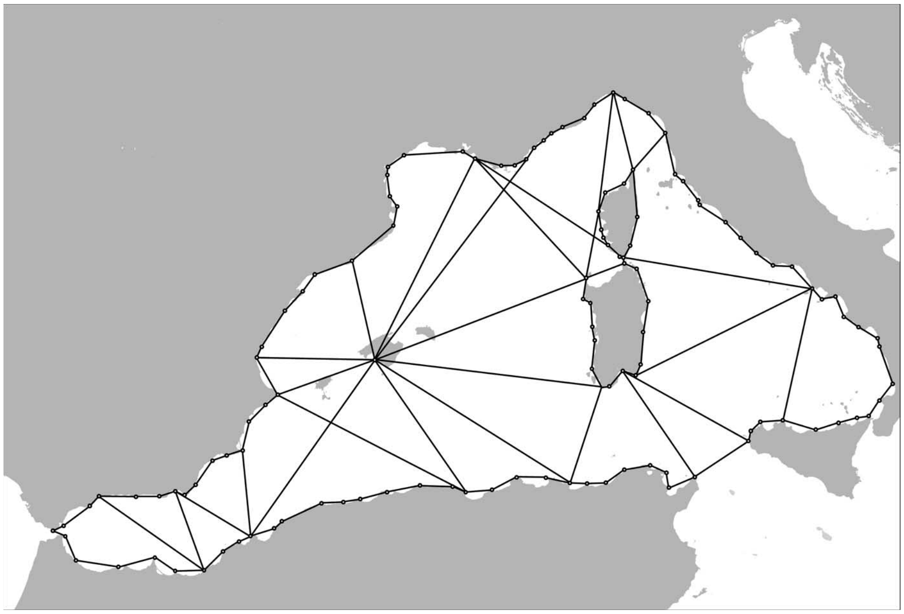

Figure 10. Geodetic network of bearings and distances in the Western Mediterranean. Distances between coastal points are of the order of 50–100 km. Similar networks may be designed for the Eastern Mediterranean and the Black Sea.

charting process, this $MSE_{\text{plane charting}}$ will be zero or very close to zero, expressing a very good fit of the synthetic portolan chart to the Mercator projection.

The reader is now asked to jump back mentally to the accuracy estimates of the real portolan charts. These were expressed in Figure 4 as RMSE values of around 11 km for each subchart. This figure was calculated by splitting the sum of the squared residuals into two components, one in an east–west and the other in a north–south direction. The *larger* of the two represents omnidirectional chart accuracy. In other words, an accuracy of 11 km should be interpreted as meaning 11 km in any direction, but it should be remembered that either in the east–west or the north–south direction the accuracy will be slightly better. For the following analysis the squares of *all* residuals—that is, both in the east–west and in the north–south direction—are required. The average of the Mean Squared Errors of all subcharts of the five charts I analyzed is 196 km^2, which we will consider to be representative for the MSE of a typical portolan (sub)chart.

The accuracy of a typical portolan chart represented by an MSE value of 196 km^2 may be considered to have three independent components. The effect of navigation accuracy on the positions of coastal points would be the main contributor. This component will be designated by $MSE_{\text{navigation accuracy}}$. The second component is the effect of the exaggeration of coastal features imposed by the cartographer (deeper bays and larger promontories), $MSE_{\text{feature exaggeration}}$. I have estimated this to be 4 km in all directions. Therefore it contributes 32 km^2 to the total chart accuracy: $MSE_{\text{portolan chart}} = 196$ km^2. *The hypothesis that the map projection of portolan charts is coincidental implies that the assumed plane-charting process does not add significantly to the error budget of the chart.* The relationship between the accuracy components may be written in a more compact form as follows:

Table 2. Components of the MSE chart accuracy in km^2, based on a nominal chart with an expected RMSE, or one-sigma accuracy of 11 km, assuming that the map projection is coincidental

	Western Mediterranean	Eastern Mediterranean	Black Sea
$\mathrm{MSE}_{\text{navigation accuracy}}$	164	164	164
$\mathrm{MSE}_{\text{feature exaggeration}}$	32	32	32
$\mathrm{MSE}_{\text{plane charting}}$	0	0	0
$\mathbf{MSE}_{\textbf{portolan chart}}$	**196**	**196**	**196**

$$\mathbf{MSE}_{\textbf{portolan chart}} = \mathbf{MSE}_{\textbf{navigation accuracy}} + \mathbf{MSE}_{\textbf{feature exaggeration}} + \mathbf{MSE}_{\textbf{plane charting}}.$$

All elements in this equation are by definition greater than or equal to zero. Alternatively, the equation may be represented in the form shown in Table 2.

However, the geodetic network computation described at the beginning of this section is based on error-free navigation measurements, without the addition of feature exaggeration. Only the $\mathrm{MSE}_{\text{plane charting}}$ component was computed. This led to the results for the three geodetic networks of the Western and Eastern Mediterranean and the Black Sea shown in Table 3.

First, the geodetic network calculation demonstrates that the distortion introduced by plane charting is far from negligible when compared to a Mercator or equirectangular reference chart. Indeed, the distortion introduced thereby is considerable; hence, at first sight the conclusion to be drawn from Table 3 is straightforward: portolan charts cannot have been constructed by means of plane charting.

However, the straightforward addition of the three accuracy components is a simplified rendering of the true situation. Two of the three components are random variables, and only the contribution by plane charting, $\mathrm{MSE}_{\text{plane charting}}$, is a constant. The addition of the three components is valid only for the *expectations* (expected values) of the random variables. The two random variables are subject to some variability with regard to their expectation. Therefore, *the question that needs to be answered is how likely it is that a fortuitous combination of random measurement errors in the distances and bearings between the coastal points might accidentally generate a Mercator-like map image for all three areas analyzed*. This problem needs to be approached through statistics. Omitting the details, let me sum up the calculation by stating that the likelihood of the scenario described in the previous sentence is negligible.[23] For the Western and Eastern Mediterranean it is impossible that a Mercator-like map image would result coincidentally from plane charting, while for the Black Sea it is not unlikely. The part of the earth's surface that is covered by the Black Sea is small enough for the map projection to be coincidental, given the navigation accuracy assumed in the analysis.

However, it makes no sense to assume that the Black Sea was charted by means of plane charting while the Mediterranean was not. Hence, the conclusion must be that the Mercator

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[23] The random variables in the accuracy budget of a typical portolan chart can be reduced to a central F-distribution and a noncentral F-distribution. The statistical testing involves the calculation of the probability of a Type II error—i.e., the probability that the chart was constructed by plane charting and that the shape of the charted coastline does not deviate significantly from the coastline on a Mercator chart.

Table 3. Expected accuracy of a typical portolan chart, taking into account the distortion introduced by plane charting

	Western Mediterranean	Eastern Mediterranean	Black Sea
$\mathrm{MSE}_{\text{navigation accuracy}}$	164	164	164
$\mathrm{MSE}_{\text{feature exaggeration}}$	32	32	32
$\mathrm{MSE}_{\text{plane charting}}$	165	323	58
$\mathbf{MSE}_{\textbf{portolan chart}}$	**361**	**521**	**254**

map projection on portolan charts, revealed by cartometric analysis, *cannot* be a coincidental by-product of the plane-charting method. The Mercator projection must therefore be an *intentional* aspect of the construction process of portolan charts—and that construction process cannot be the plane-charting process. To be sure, the conclusion applies to the partial charts from which the Mediterranean portolan chart was constructed as a mosaic. There is no known alternative process that would coincidentally produce a Mercator (or other) map projection.

The results of the analysis I have presented must lead to rejection of the entire hypothesis of a medieval origin for portolan charts. On the basis of current knowledge of the state of science in the Middle Ages, it must be concluded that the construction of portolan charts was beyond the capabilities of medieval cartographers, mariners, and intellectual clerics. The role of the medieval cartographer in the creation of the accurate Atlantic, Mediterranean, and Black Sea coastlines appears to be limited to copying older partial charts, creating a mosaic, and exaggerating coastal features.

MERCATOR OR EQUIRECTANGULAR PROJECTION?

To analyze five charts with the assumption that they are based on the Mercator projection and then to conclude that they are indeed based on the Mercator projection might look like circular reasoning. However, several studies have already established that, with respect to portolan charts, a cylindrical map projection is the best-fitting *type* of map projection, as such a projection will render the meridians as a lattice of straight, parallel lines. A conical map projection would result in the meridians converging toward the north, which is not the case with portolan charts. In addition, the correspondence of the residuals of the piecewise fit to the Mercator projection of the Dulcert chart (1339) with the normal or Gaussian error distribution suggests that the Mercator projection or a Mercator-like projection fits very well, as shown in Figure 3. Other types of map projection are less likely, as Loomer's study demonstrated.[24]

Two types of cylindrical map projection are candidates for portolan charts—namely, the Mercator projection and the equirectangular projection. The latter is also known as the equidistant cylindrical projection. On a Mercator chart the spacing between parallels at intervals of equal number of degrees increases logarithmically toward the poles. The Mercator projection is in principle true to scale only at the equator. The parallels and meridians thus span a rectangular graticule. The higher the latitude, the more the rectangles are stretched in a north–south direction. On the other hand, the equirectangular projection generates a lattice

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[24] In particular, Loomer, "Cartometric Analysis of Portolan Charts" (cit. n. 4), p. 133, suggested that a cylindrical projection best fit the portolan charts; for his demonstrations that other types of projection are less likely see pp. 146, 154, 158.

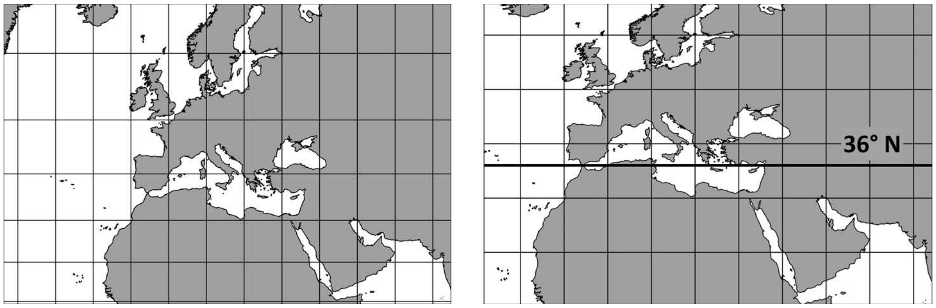

Figure 11. Map of Europe on the Mercator projection (left) and on the equirectangular projection (right) with true-to-scale parallel of 36° N latitude and a graticule of 10° latitude and longitude intervals.

of rectangles with a constant height-to-width ratio. Only two parallels are thus projected true to scale, symmetric with respect to the equator, but all meridians are true to scale. This map projection was known in antiquity: it was used by Claudius Ptolemy's predecessor Marinus of Tyre. Ptolemy states that Marinus proposed an equirectangular projection of which the true-to-scale parallel was the "parallel of Rhodes," at approximately 36° N. This results in a spacing of the meridians that is 0.8 times the spacing of the parallels, as shown in Figure 11.

For an area with a limited latitude extent, such as the Mediterranean region, an equirectangular projection may be designed that closely approximates the Mercator projection. When a modern map using the equirectangular projection of—for example—the Western Mediterranean is placed on a light table and is overlaid with a modern map of the same scale and the same area that uses the Mercator projection, the differences in the depicted coastlines will be clearly visible, because modern maps are exceedingly accurate. For a portolan chart, however, although it is very accurate in the context of its time, it is difficult if not impossible to distinguish the Mercator projection from the equirectangular. Almost equal MSE values will be computed after the best-fitting process is applied to these two projections. For smaller areas such as the Black Sea it is impossible to distinguish the two. Nevertheless, portolan charts share more characteristics with the Mercator projection than with the equirectangular projection.

Once it is understood that it is difficult to distinguish the Mercator projection from the equirectangular projection, though, it is tempting to consider the equirectangular projection more likely than the Mercator projection as the underlying projection of portolan charts because its graticule is simpler to construct. It was also known in antiquity and therefore does not constitute an apparent anachronism, while positing the Mercator projection as a basis for portolan charts does. Construction of the graticule (the lattice of meridians and parallels) of the equirectangular projection is indeed much more straightforward than construction of the graticule of the Mercator projection, because the latter contains a logarithmic function. The equirectangular graticule may be constructed simply with a ruler and a pen. However, the advantage disappears when a chart is constructed from a set of surface geometric measurements—which, we have to assume, is how the first portolan chart was constructed. In order to draw a chart on the equirectangular projection, the cartographer would have to apply latitude-dependent corrections not only to distances but also to directions, so the latitude of each pair of points therefore needs to be measured as well. Moreover, these corrections are so impractical that the relevant formulas cannot be found in modern geodesy textbooks. By contrast, all that needs to be done to produce the Mercator projection is divide all distances by the cosine of the mean latitude of the two end points of the distance and leave any directions uncorrected (except for magnetic declination, but that is not a map projection characteristic). This also requires measurement of latitude, of course, but apart from that it is in principle a good deal easier to construct a Mercator chart from such surface measurements than an equirectangular chart. The alternative would be first to calculate latitude and longitude of all points along the coastline from the surface measurements. Plotting those in a preconstructed equirectangular graticule would then be straightforward, but the complication of that option lies in the calculation of the latitudes and longitudes for all points. To sum up: when the starting point of mapping is a set of geometric measurements (directions, distances, and bearings) between points along the Mediterranean coast, the Mercator projection is the simpler projection from a construction perspective.

ADDITIONAL EVIDENCE AGAINST A MEDIEVAL ORIGIN

The results from the previous sections are sufficient to reject a medieval origin for portolan charts unequivocally: even with a perfect set of measurements of bearings and distances covering the Mediterranean it is impossible to generate a chart with the characteristics of a portolan chart by means of plane charting. Questions regarding the timely introduction of the magnetic compass and the quality of medieval navigation have therefore become irrelevant. Nevertheless, for the sake of thoroughness, it is worth looking at these factors.

It was stated earlier that there is no consensus as to the role of the magnetic compass among researchers who study portolan charts. Was its usage in the Mediterranean sufficiently widespread by the time the first portolan charts appeared to permit the assumption that it may have played a role in their construction—that is, in the collection of the body of navigation data that is presumed to have formed the empirical basis of portolan chart construction? Some researchers believe it was; others do not; the majority simply ignore the timing issue.

The earliest reference to the compass in Europe dates from 1187, when Alexander Neckam mentions its use on dark nights and during the day when the sky is overcast.[25] He describes this use not as a novelty, but as an established practice. The compass he describes is a so-called "floating compass," a needle stuck crosswise through a piece of cork or straw, floating in a bowl of water. The needle was magnetized by moving a piece of lodestone in circles above the bowl with the floating needle and then withdrawing it suddenly. This type of compass, usually referred to in documents from that period as the "needle" ("*acus*"), was only a rough indicator of north and would have been unsuitable for making quantitative measurements of a ship's heading. The next stage in the development of the compass occurred when the needle was placed on a vertical pin, allowing it to rotate freely. To protect this delicate construction, needle and spindle were placed in a small wooden box, and thus it is that the compass acquired the name "*buxola*" or "*bussola*," which literally means "small box." This word appears to refer to the compass as a single unit rather than a collection of separate features, as was the case with the floating compass. The first description of such a compass occurs in 1269, when the Frenchman Pierre de Maricourt, also known as Petrus Peregrinus, mentions it in a letter to a friend.[26] Peregrinus also notes that the cardinal directions and even a degree scale may be marked on the rim of the wooden box containing the needle. Furthermore, he

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[25] Thomas Wright, ed., *A Volume of Vocabularies* (London, 1857), p. 114. The text included in this volume is Alexander Neckam's *De Utensilibus*, written between 1175 and 1183.

[26] Peter J. Smith, "Petrus Peregrinus' Epistola: The Beginning of Experimental Studies of Magnetism in Europe," *Earth Science Reviews*, 1970, 6:A11–A18, esp. p. A13.

describes an alidade as part of the unit. In principle such an instrument would be suitable for making sufficiently accurate measurements—for example, to coastal landmarks. The final medieval improvement to the compass was made when the compass card marked with a compass rose of thirty-two "winds" was fixed to the needle, such that the card would rotate freely with the needle. Such a compass is called a "mariner's compass," and its great advantage is that it allows the ship's heading to be read directly on the instrument. It is unclear when this innovation was made. The term "*buxola*" or "*bussola*" gradually replaced the term "needle" ("*acus*"), and this change is generally associated with the transition from the simple floating compass to the compass described by Peregrinus or the mariner's compass. The key question is *when* this transition took place. Peter Pelham collated references to the compass from contemporary literature and found that the term "*buxola*" (with spelling variants) begins to appear only in the middle of the fourteenth century. In a more recent study, Ramon Pujades, who investigated notarial records in the archives of Catalonia, Valencia, Majorca, Genoa, Sicily, and Venice, arrived at the same conclusion; he found that the first recorded use of the term "*bussola*" in these documents occurs in 1349.[27]

Therefore it appears very unlikely that a compass of the sort described by Peregrinus or the mariner's compass was in widespread use aboard ships before the middle of the fourteenth century. That is far too late for the instrument to have played a role in the presumed collection of a large body of navigation data across the whole Mediterranean, the Black Sea, and the Atlantic coast of Europe. Nevertheless, the possibility cannot be excluded that Peregrinus's invention was used aboard ships on a much more limited basis and perhaps in the establishment of the orientation of the first subchart, from which the mosaic would have been compiled. The most likely candidate for that is the Western Mediterranean subchart, which has the most consistent orientation of all subcharts among the five portolan charts analyzed (see Figure 7).

The late availability of a suitable compass undermines the hypothesis that a large body of navigation data was collected from which a chart—*any* chart, not just one on the Mercator projection—could have been constructed. Without the availability of a suitable compass, no geodetic framework could have been measured from which the shape of the Mediterranean and Black Sea coasts might have been constructed. In theory, one might imagine a *trilateration* network—that is, a framework consisting of distances only between coastal points—but this would have to have been an extremely dense network, with many distances measured over the open sea, as every key point along the Mediterranean coast would have to be the corner point of one or more triangles. Triangles built up from successive series of three successive coastal points located nearly on a straight line would not be acceptable. Therefore a trilateration network would depend on a large number of (long) cross-sea distance measurements in many directions, the measurement of which would have been hampered by the inability of medieval ships to sail in directions at significant angles to the Mediterranean's prevailing northerly to northwesterly summer winds. Furthermore, it is unlikely that sailors would have been able to sail a straight course without the help of a direction-indicating instrument.

Nonetheless, in order to ensure that my conclusions are independent of the above arguments, I conducted my analysis of the compatibility of the Mercator map projection with

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[27] Peter T. Pelham, "The Portolan Charts: Their Construction and Use in the Light of Contemporary Techniques of Marine Survey and Navigation" (M.A. thesis, Victoria Univ. Manchester, 1980), pp. 64–65; and Pujades, *Les cartes portolanes* (cit. n. 3), p. 444.

the assumption that the compass *was* in widespread use early enough to have contributed to the hypothetical body of navigation data.

Another important question concerns the accuracy of medieval navigation— excluding visual navigation from landmark to landmark, as that method is not quantitative. For navigating across stretches of open water, dead reckoning was the only option for quantitative navigation. Until the invention of the English log in the sixteenth century, ship's speed, the basis for the calculation of distance, was estimated in subjective ways. From antiquity to the Middle Ages, progress was measured in terms of "day's sailing," for which sometimes a nominal equivalent in a unit of length existed. Ibn Jubayr, a twelfth-century Arab traveler, states that Arab sailors used the *majra*, a standard figure for a day's sailing that they equated to 100 Arab miles (about 190 km).[28] More precise estimation methods are only known from descriptions in later centuries and have to be extrapolated back to the Middle Ages. Such methods assume that the ship's speed was estimated and then multiplied by time elapsed to obtain the distance the ship had traveled over that interval. Navigators estimated the ship's speed either from experience— by looking at the bow wave of the ship, the froth created by the ship, and the way the sails set as a result of the pressure of the wind— or by a slightly less subjective but still crude method that may be called a *gunwale log*. This assumes two markers on the ship's railing or bulwark, one close to the bow and the other near the stern, separated by a calibrated distance. The navigator would have an assistant throw a chip of wood into the water at the bow marker and then estimate the time it took to sight the chip across the stern marker by reciting a rhyme or ditty, pacing down the deck, counting his steps, or taking his pulse. Although not improbable, there is no evidence for the use of either method in the twelfth and thirteenth centuries.

I developed a quantitative model that takes into account the main factors contributing to the accuracy of the putative medieval dead-reckoning navigation method.[29] This model is (on purpose) highly optimistic, as it assumes that medieval sailors diligently estimated their ship's progress in this way at every four-hour watch interval. The model also assumes that errors were canceled out to a large degree because successive independent interval estimates were made over the course of a long journey. Furthermore, it assumes that the ship traveled along a perfectly straight (rhumb) line to the end point of its route. Even with the most optimistic assumptions, the resulting standard deviation is 17 percent of the entire distance. A figure of twice the standard deviation, which corresponds to a confidence level of 95 percent, equals 34 percent of the distance. That is quite inaccurate. The factor that is chiefly responsible for this inaccuracy is the lack of an objective time standard. The intuitive assumption, mentioned at the beginning of this essay, that some form of accuracy improvement would have been needed is thus borne out by this simulation model.

The question of how accurate such measurements needed to be to create a portolan chart is actually irrelevant. As I have shown, with the medieval method of chart construction—plane charting—as the only viable option, the shape of the Mediterranean coastline on a portolan chart could *never* have emerged, regardless of the navigation accuracy. However, one might be interested to know what navigation accuracy would have been required, had the hypothetical medieval cartographer been able to correct the observations to obtain the Mercator projection. As it cannot be assumed that a medieval cartographer would even have known

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[28] Ibn Jubayr, *The Travels of Ibn Jubayr*, trans. Roland Broadhurst (New Delhi: Goodword, 2007), p. 26.

[29] Nicolai, *Critical Review of the Hypothesis of a Medieval Origin for Portolan Charts* (cit. n. 2), pp. 151–161, 439–449 (Section 5.9 and Appendix III).

about these corrections, the question is purely hypothetical. Additionally, he would have needed the mean latitude along every distance measured, but Mediterranean navigation never used latitude determination as a tool. If that had been used, portolan charts would not have been rotated with respect to true north by the anticlockwise angle of about 9 degrees, as was mentioned at the beginning of this essay. However, had he known how to correct his distances and had he known the mean latitude at which each distance had been measured, the accuracy that is demonstrated by portolan charts would have necessitated position determination of coastal features of about 9 to 10 km, whereas the accuracy model I developed leads to an estimated positional accuracy of coastal features of 60 km for the Western Mediterranean, 120 km for the Eastern Mediterranean, and around 70 km for the Black Sea—in all cases based on highly optimistic assumptions.[30] Without some means of improving the accuracy of distance and bearing estimates, the construction of any chart having the accuracy demonstrated by portolan charts would have been impossible.

It is nowadays considered almost self-evident that the accuracy of a measurement may be improved by taking a series of observations and then calculating the arithmetic mean. However, that process was not self-evident in the Middle Ages. According to the statistician Robin L. Plackett, the astronomer Tycho Brahe was the first to use this concept, toward the end of the sixteenth century; it took another century before the fact that calculation of the mean gave a more precise value than a single measurement was understood in wider scientific circles. Steven M. Stigler is even more cautious, stating that "by the middle of the eighteenth century at least one statistical technique was in frequent use in astronomy and navigation: the taking of a simple arithmetic mean among a small collection of measurements made under essentially the same conditions and usually by the same observer."[31] An understanding of this technique in medieval times cannot therefore be assumed. Although many researchers have assumed that the calculation of the arithmetic mean from a series of single measurements would be a plausible way in which the accuracy of bearing and distance estimates could have been improved, this is a clear example of presentist thinking: it may be obvious in the twenty-first century, but it certainly was not in the thirteenth. Assumptions that a more "intuitive" central value might have been determined, without actually calculating the mean, also have to be rejected. In that period any such advanced treatment of a series of single measurements is equally unlikely: the basic understanding of the concept of "random error" simply did not exist in the Middle Ages. An alternative hypothetical schema, pushing this process of accuracy improvement entirely into a graphic reconciliation method, would have been considerably more difficult. This technique became an option only in modern geodesy.

CONCLUSIONS

1. Portolan charts are confirmed to be mosaics of subcharts, each of which is quite sophisticated, having a mean point accuracy of approximately 10–12 km. The conclusion that they are mosaics of partial charts is not new; confirmation of the high accuracy of the subcharts is. Also new is the conclusion that the mosaic was probably constructed by a process of fitting together overlapping sections of coastline visible on the partial charts.

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[30] *Ibid.*, pp. 374–380 (Section 9.8: "Network Adjustment #1—Accuracy").

[31] Robin L. Plackett, "Studies in the History of Probability and Statistics, VII: The Principle of the Arithmetic Mean," *Biometrica*, 1958, 45:130–135, esp. pp. 131, 132: and Steven M. Stigler, *The History of Statistics: The Measurement of Uncertainty before 1900* (Cambridge, Mass.: Harvard Univ. Press, Belknap, 1998), p. 16.

2. The shape of the Mediterranean coastline as rendered on a portolan chart is different from the shape of the coastline constructed from plane charting to a statistically significant degree. The charts therefore cannot have been constructed using the plane-charting method.
3. The partial charts are based on a map projection. As this map projection cannot be a coincidental by-product of a presumed plane-charting technique (see conclusion 2), it can only have been applied intentionally as part of the construction process. This map projection is most likely the Mercator projection, but an alternative is the equirectangular projection, which in the limited latitude range of the Mediterranean can hardly be distinguished from the Mercator projection.
4. The magnetic compass, in a form that would have allowed it to be used as a tool in the position determination of coastal points, appears to have come into widespread use only during the first half of the fourteenth century. It therefore could not have played a role in the construction of these charts, but it may have been used in the establishment of the main orientation of portolan charts.
5. The navigation accuracy with conjectured medieval methods is too poor for such data to have been the basis of the construction of any map as accurate as portolan charts. This is true even when highly optimistic assumptions are made about the navigation process and environmental conditions.
6. Methods to improve the accuracy of single navigation data estimates by averaging cannot be posited as an argument to explain the accuracy of portolan charts. The awareness that estimates of a bearing or distance between two points may be improved by calculating the arithmetic mean of a series of single measurements entered scientific practice only in the course of the seventeenth century.
7. The main conclusion is that portolan charts are not the primitive, projectionless charts that they have been believed to be. It seems reasonable to assume that mosaics of partial charts were created during the Middle Ages, but the construction of the partial charts themselves was well beyond the capabilities of medieval cartographers. These partial charts must date from a period before the Middle Ages.

WHERE DID PORTOLAN CHARTS COME FROM?

If portolan charts are not an original creation of medieval Italian mariner-cartographers, where did they come from— or, rather, where did the original partial charts come from? The charts themselves do not provide any clue to a possible answer, nor does contemporary documentation. What follows therefore cannot be anything but an educated guess.

The most likely scenario explaining their appearance in medieval Italy seems to be that Italian merchants acquired the source charts through their trade with Byzantium. The Byzantine Empire itself is an unlikely origin point for these charts. In view of their sophistication and accuracy, as demonstrated above, construction of the original source charts requires a civilization with sufficient mathematical, geodetic, and cartographic expertise and also a high level of instrument making. To the best of our knowledge, Byzantine culture did not even come close to satisfying these requirements. Even so, the role of Byzantium in preserving the legacy of antiquity is undisputed. Byzantine mariners may even have used these charts themselves, although it is doubtful that charts of high accuracy would have been necessary for trading journeys inside their own empire.

Italians may have seen greater potential for the use of these charts. There is even an indirect indication that they may have been used during the Crusades and therefore may have existed as early as the twelfth century. John H. Pryor has pointed out that a step change in crusading logistics occurred in the twelfth century.[32] While troops and horses for the First Crusade traveled overland to Palestine, maritime transport (including night sailing) developed during the twelfth century, so that for the Second and Third Crusades large numbers of soldiers, knights, and horses were transported to the Holy Land by ship. Since no significant developments took place in shipbuilding during that period, a new development in navigation may have a certain *prima vista* plausibility.

What then about an origin for the source charts in Greek antiquity? If the standard hypothesis of a medieval origin required evidence, then so would any new hypothesis that the source charts may have been constructed in antiquity. As has been argued above, the construction of charts covering such a large area constitutes a huge, complex, and advanced geodetic-cartographic task. At this point there is simply no evidence that the Greeks (or any other ancient civilization) would have possessed the required knowledge and instruments—or, for that matter, that they would have had any reason to perform such a task. Successful proof that portolan charts are Greek in origin would overturn our current ideas about ancient Greek knowledge and skills, while the absence of such proof leaves us with a highly unsatisfactory mystery—one that can be resolved only through empirical evidence that is as yet missing completely. Our current ideas about Greek knowledge cannot be regarded as fully settled, however. The discovery of the mysterious Antikythera mechanism, which contains a complicated system of gears constituting what may be an early analogue astronomical computer, has demonstrated that sufficiently.[33] The research that has been carried out on this mechanism so far may provide a stimulus to look even more critically at our established ideas about Greek science. But whether such a critical look will help us resolve the enigma of the portolan charts must remain anybody's guess, my own included.

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[32] John H. Pryor, "A Medieval Maritime Revolution: The Logistics of Crusading by Sea, 1097–1204," paper presented at College Station, Texas, in 2007 (made available by the author).

[33] Jo Marchant, *Decoding the Heavens: Solving the Mystery of the World's First Computer* (London: Windmill, 2009).