Medieval Portolan Charts, a Geodetic and Historical Mystery

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SUMMARY

The sudden appearance of portolan charts, realistic nautical charts of the Mediterranean and Black Sea, at the end of the thirteenth century is one of the most significant events in the history of cartography. By using geodetic and statistical analysis techniques, these charts are shown to be mosaics of regional charts that are considerably more accurate than has been assumed. Their accuracy exceeds medieval mapping capabilities. These regional charts show a remarkably good agreement with the Mercator map projection. It is demonstrated that it is very unlikely that this map projection is an unintentional by-product of the charts' putative medieval construction, as is widely believed. While the physical charts are without doubt medieval, the possibility is eliminated that the charts are original products of a medieval Mediterranean nautical culture, which until now they have been widely believed to be. Their true origin must lie considerably further back in time.

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1. SETTING THE SCENE

The sudden appearance of portolan charts in the late medieval Mediterranean world of maritime commerce at the end of the thirteenth century ranks as one the most significant events in the history of cartography. Their extraordinary realism contrasts sharply with the qualitative character, often with religious overtones and classical elements, of the contemporary *mappae mundi*. They represent an unprecedented step forward in cartography, which set the tone for mapping in the Age of Discovery and beyond. Portolan charts are the first maps after Ptolemy (c. AD 150) to have been drawn to scale.

Apart from their evident significance for the history of cartography, they also constitute a historical, geodetic and cartographic mystery that has so far proven to be unsolvable, notwithstanding claims to the contrary, often made with a confidence that is unwarranted. Nevertheless, an admission, still valid, was made that we simply do not know how these charts were made and even who made them (Campbell 1987):

> ‘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’

Whilst conceding that it is not understood how these extraordinary charts were constructed, experts on portolan charts show an understandable reluctance to question the assumption of a European medieval origin of portolan charts, because the charts contain not a trace of a possible origin in either classical Antiquity, the Arabic-Islamic world or the Byzantine empire. They share no characteristics with Ptolemaic maps from late Antiquity. Only a few Arabic-Islamic portolan charts are extant and these appear to be copies of fifteenth century European charts. So, by a process of elimination, a European medieval origin is what remains. However, recent research has proven the consensus view incorrect. By applying numerical analysis methods, familiar to geodesists and surveyors, I have been able to prove that these charts cannot be medieval. Rather than being relatively primitive medieval cartographic products they are geodetically constructed charts of a higher accuracy than has been acknowledged before. The construction of such sophisticated charts was far beyond the capabilities of medieval cartographers. The charts cannot be falsifications of a later date; too many survive for that to be an option and the impact they had on later cartography is too clearly visible.

2. WHY ARE PORTOLAN CHARTS ‘STRANGE’?

Portolan charts are manuscript charts drawn on vellum, a fine quality of parchment. Their dimensions were often dictated by the size of skin, typically about 100 cm by 75 cm. That makes their scale approximately 1:5,500,000; 1 cm on the chart equates to 55 km in the real world. The earliest portolan charts show the Mediterranean, the Black Sea and often the Atlantic coasts from Morocco to the south coast of England with remarkable accuracy. Although the North Sea and the Baltic Sea are often also depicted, these areas lack the realism and detail of the core area just described. Portolan charts are clearly nautical charts and as such constitute a new cartographic genre. Their characteristics became hallmarks of all nautical charts until well into the eighteenth century. The names of ports and landmarks are written at right angles with the coastline on the land side; important names are red and the remainder black.

Figure 1: Portolan chart by Angelino Dulcert, 1339 (Bibliothèque nationale de France)

A striking characteristic of portolan charts is the pattern of the straight lines drawn apparently at random across the entire chart. On closer inspection they form a regular, ingenious pattern, known as a *wind rose,* created by interconnecting sixteen regularly spaced points on a circle, which covers the larger part of the chart. This results in a total of 32 directions. The chart in figure 1 contains two wind roses, one on the western half of the chart and one on the eastern half, tangent to one another in the middle of the chart. The wind rose lines were colour-coded in black, red and green and named after the eight main ‘winds’ (directions) that the medieval sailor distinguished. The colour-coding would have facilitated the selection of the correct compass bearing when planning a voyage. The wind roses are aligned with the the cardinal directions and thus provide an absolute orientation to the charts. This reveals that the entire coastline image is rotated anticlockwise by about 9°. This angle remains more or less constant until about 1600 AD, when portolan charts oriented to true North begin to appear.

Most surviving charts were decorated with colourful city vignettes and pennants and were probably intended for prestige and display by their (wealthy) owners. But there is sufficient evidence of on-board use of portolan charts, presumably as a navigation aid (Pujades 2007). Most of those would have had a limited lifetime in the damp and salty offshore environment and they would probably lack the decorative elements mentioned.

Portolan charts have a number of curious characteristics. They appear out of nowhere, almost fully developed; no precursors or prototypes are known. Consequently, there is no ‘bread crumb trail’ in the historical record that might shed light on how these charts were constructed and how they acquired their high accuracy. Equally strange is that hardly any development appears to have taken place *after* their first appearance: their key characteristics do not change. It is clear that they were copied from chart to chart. Portolan charts did not become gradually more accurate, nor were their typical shortcomings and defects resolved over time. Shortcomings they do have: they exhibit regional scale and orientation differences that are subject to some change, but no gradual improvements are visible. Other shortcomings concern persistent errors in the details of the coastline. This is odd, because if medieval cartographers were capable of making such accurate charts, why did not the same skills permit them to resolve these shortcomings? The strangest property of these charts, apart from their accuracy, is the fact that the image of the coastlines of the Mediterranean, the Black Sea and the Atlantic coasts closely resembles the map image of a modern map or chart on the Mercator projection. The Mercator projection was invented by Gerard Kremer in the middle of the sixteenth century, whilst the oldest extant portolan chart, the so-called Carte Pisane, is dated to about 1270. Moreover, the accuracy of portolan charts is much higher than that of any contemporary or earlier map. It is even higher than the accuracy of maps from the centuries that followed. It would take until the eighteenth century before new maps of comparable accuracy were produced.

3. EXISTING IDEAS ABOUT THE ORIGIN OF PORTOLAN CHARTS

Despite the abundance of different hypotheses on the origin and the construction method of portolan charts – these two aspects are interrelated – experts do agree broadly on a number of things. Firstly, there is near-unanimous agreement that portolan charts are based on actual measurements, rather than on a mental image of the world. Their accuracy leaves no room for other explanations. Contemporary maps, the European *mappae mundi* and Arabic-Islamic maps, are based on a mental model of the world. There is almost unanimous agreement that portolan charts are original products of medieval European culture.

Because the charts appeared in the maritime-commercial milieu, the commonly accepted hypothesis is that medieval mariners made measurements of distance and course bearing during their trading voyages. The data collected in that way is assumed to have provided the geometric basis of chart construction. Most authors see confirmation of this hypothesis in the fact that the anticlockwise rotation angle of about 9° that all charts exhibit roughly agrees with magnetic declination in the Mediterranean in the thirteenth century, estimated from paleomagnetic models. Magnetic declination is the angle between true north and magnetic north at any location; it varies by location and over time. Some researchers even see the anticlockwise rotation of portolan charts as incontrovertible proof that the magnetic compass played a key role in the construction of these charts. After this point most hypotheses become vaguer. Those that are specific enough usually postulate central collation of all data somewhere along the Ligurian coast of Italy. Genoa and Pisa are prime candidates, because it is from this area that the oldest extant portolan charts originate and both cities were dominant in maritime trade. Additionally, some unspecified schema of accuracy improvement is assumed, often expressed in vague terms such as 'progressively better estimates of distances became available over time', but some authors explicitly mention a process of averaging.

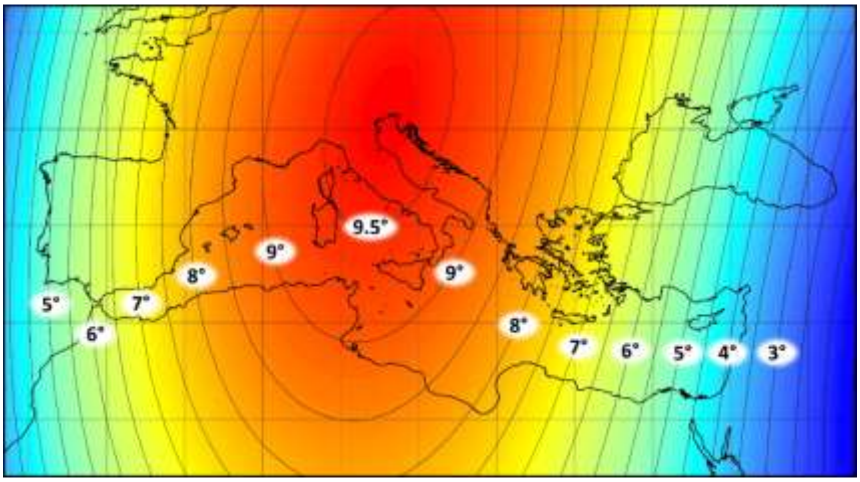

Figure 2: Magnetic declination from the model CALS7k.2 for the year 1250 (the positive values indicate an easterly magnetic declination)

Whatever the process of accuracy improvement might have been, the next step that is assumed is the drawing of the first portolan chart from these improved estimates of distance and direction. This presumes organisation and sharing of the corpus of navigation measurements. It is assumed by many that an intermediate role was played by so-called *portolans*, written sailing instructions containing navigation data of the form: 'From A to B, so-many miles along such-and-such a course'. This assumed causal relationship has given portolan charts their name, which is therefore a modern invention. In the Middle Ages they were known under a variety of names, but not as 'portolan charts'. More recently some authors have become more cautious regarding the relationship between the two following recent proof of a reverse relationship by statistical analysis: the data in the oldest known complete portolan of the Mediterranean and Black Sea (1296) was scaled from one or more portolan charts (Nicolai 2016).

Only the so-called *plane charting* technique may be assumed for the construction of the chart; distances and bearings were transferred to the map as if the earth were flat. More sophisticated methods cannot be assumed to have been available in the Middle Ages. Magnetic declination was not known and its effects on compass bearings was not recognized. Furthermore, it is assumed that some form of graphic adjustment was carried out by the cartographer in order to deal with the contradictions in the data due to the inevitable random errors in the measurements. The effects of ignoring earth curvature are generally downplayed as 'negligible' or 'relatively minor'. Map historian David Woodward was fairly specific on how he though this process of chart making might have taken place (please note that he doesn't mention directions):

> 'The cumulative experience of several centuries of coastal and other shipping in each of these (sub-)basins could have led to the independent recording of traditionally known distances. The average distances derived from both coastal traverses and cross-basin routes could then have been used in the construction of a series of separate charts of the individual basins. If these routes were plotted to form networks in each of the basins, each network might have assumed the form of a self-correcting closed traverse of each basin. The rigidity of this structure would, however, have depended on the availability of cross-basin distances, acting as braces to the framework. It is thus postulated that some system of empirical or stepwise graphic method of correcting these frameworks was used to achieve a "least-squares" result.' (Campbell, 1987).

Woodward was well aware that the method of least squares was not available in the Middle Ages; his intention is to suggest that all data contradictions would have been resolved by distributing them over the entire network of coastal points using a less formal graphic method. Most researchers approach this explanation intuitively and accept it as true. No one has checked whether it is feasible or realistic.

A recent trend appears to be to deliberately avoid any specific statements about the charts' origin and construction method. Portolan charts are then seen as the '… products of medieval Mediterranean culture in its entirety, characterised by multiple cultural exchanges' (Gautier Dalché, The accuracy of the charts is downplayed and the close agreement with the Mercator projection is glossed over, as are other historical facts that do not fit this explanation.

Controversial aspects of the charts that cry out for a rational explanation are firstly their accuracy and secondly the regional scale differences on each chart. Finally, for me, as a geodesist, the key characteristic to be explained is their good agreement with the Mercator projection. As explained above, the consensus on the accuracy of the charts is that some form of averaging took place, either as the calculation of the arithmetic mean of series of observations of the same distance or bearing, or the averaging was integrated in the assumed graphical adjustment of all data when the first chart was plotted. There is considerable consensus that the scale differences are caused because the sub-basins of the Mediterranean were charted first and the resulting partial charts were stuck together in a second step. Historians of cartography are virtually unanimous in their opinion that the Mercator projection is an unintentional by-product of the plane charting process and unrecognized magnetic declination. This is considered intuitively to be true. Apart from my analysis of portolan charts that assumption has never been tested.

4. THE ACCURACY AND COMPOSITION OF PORTOLAN CHARTS

The close agreement of the coastal outlines on portolan charts with the Mercator projection also enables the accuracy of these charts to be estimated. A best fit of the portolan chart with a modern Mercator chart needs to be established first. The residual 'errors' of points on the portolan chart from corresponding points on the Mercator chart may be considered to be representative of the accuracy of the portolan chart. This accuracy can be captured in the concept Mean Square Error (MSE), or rather the square root of that, the RMSE. The RMSE

values of the latitude residuals and the longitude residuals were calculated separately. The larger of the two represents the accuracy of the regional chart (Nicolai, 2016).
Several researchers conducted a numeric analysis of one or more charts, but all approached the charts as single, coherent units. If portolan charts are mosaics of partial charts, each with its own different scale, that approach is methodologically incorrect. In my own PhD research, I subjected five early charts, later extended to six, to cartometric analysis as described above, but treated them as mosaics. All cartometric analysis begins with the identification of a large number of *identical points*, that is, pairs of corresponding points on the portolan chart and the reference Mercator chart of which the coordinates are measured. I established the boundaries of the partial charts empirically, by statistical testing, identifying groups of identical points that formed coherent subsets. I associated each coherent subset with a regional chart. This yielded some surprising results:

- the accuracy (RMSE) of each subset is surprisingly good, with an average of 11.3 km (figure 3); this equates to about 2 mm on the Dulcert portolan chart;
- there are differences in scale an orientation between the regional charts (figures 4 and 5);
- the boundaries between the coherent subsets of points do not align with the boundaries between the sub-basins of the Mediterranean;
- there were overlaps, but also some gaps between adjacent subsets of identical points.

While it can be confirmed that portolan charts are mosaics of partial charts, their accuracy leads to renewed questions of how they attained this accuracy.

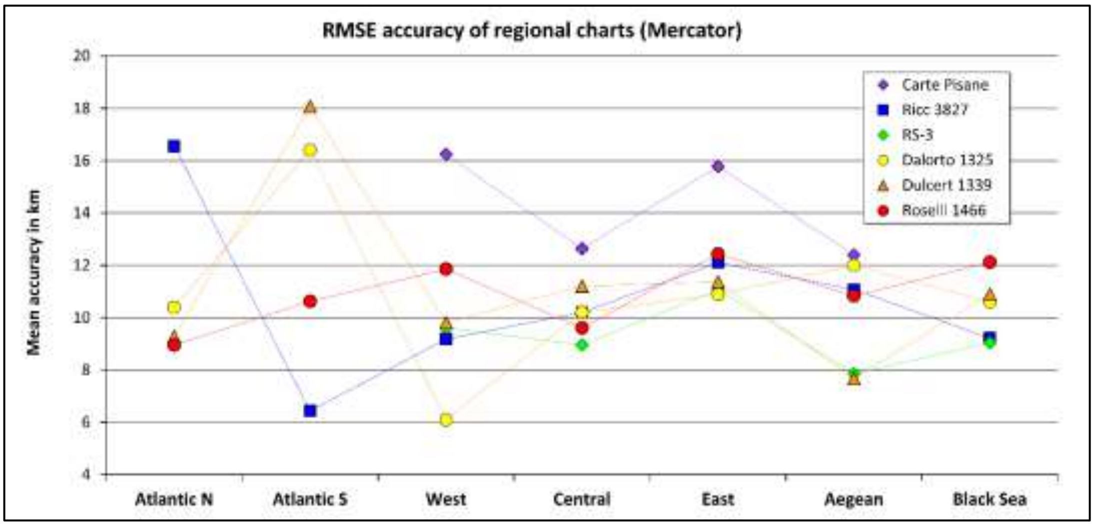

Figure 3: Mean accuracies per sub-chart for six charts analysed

The overlaps between adjacent regional charts, notably those between the regional charts covering the Mediterranean, were probably used to fit the regional charts together to a mosaic. The overlap zones were therefore adjusted by the cartographer to achieve smooth joins.
The assumption of most experts is that distance was measured by estimating the speed of the ship at regular intervals, for example at every change of watch, that is, about four hours. No instrument was available to measure speed until the last quarter of the sixteenth century. Only

subjective methods of estimating speed could have been used in the thirteenth century. It is usually assumed is that a wood chip was thrown into the water at the bow of the ship. The navigator would estimate the time it took for the stern of the ship to pass the wood chip. He did this by taking his pulse, saying a rhyme or pacing up and down the deck, because no instruments to measure such short time intervals (nominally about 10 seconds) were available at the time. Two markers on the bulwark, at the bow and stern respectively and at a calibrated distance apart, might have been used as baseline.

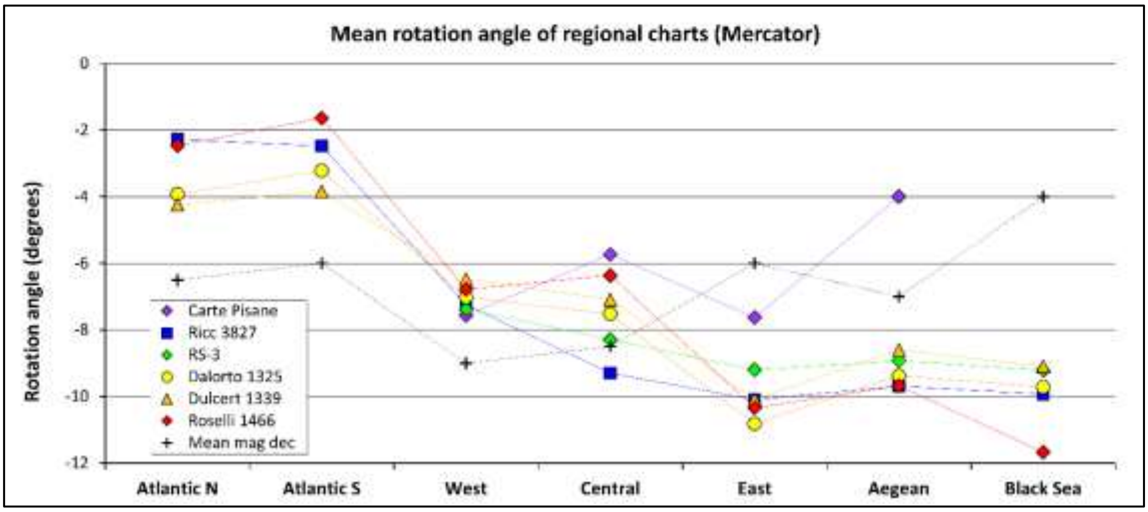

Figure 4: Mean rotation angle per regional chart of six charts analysed. Mean magnetic declination for the relevant region is indicated by a '+' symbol

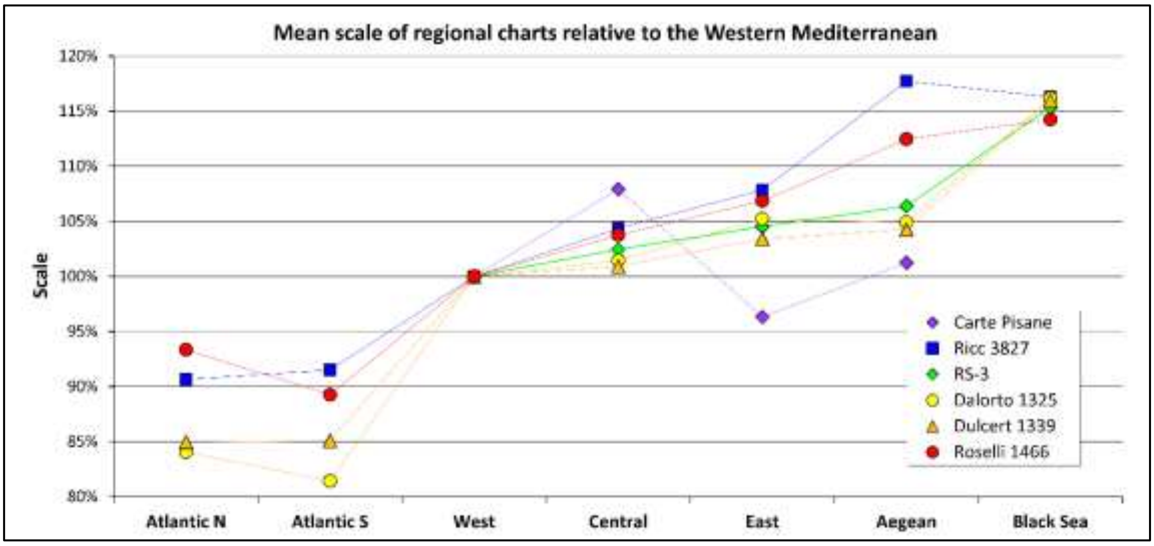

Figure 5: Mean scale per regional chart of the six charts analysed

It will be clear that such a speed estimate would have had a very limited accuracy; furthermore, considerable extrapolation would have involved to convert this speed estimate to an estimate of the distance sailed during the watch period and then on the distance for the whole journey. I developed a statistical model for medieval navigation, taking into account all relevant phenomena that would have influenced this process of distance estimation. The result is that, even when many effects are ignored and highly optimistic assumptions are made, distance cannot be estimated in this way better than about one third of the distance travelled, which refers to the 95% confidence level (Nicolai 2016). Available space prevents a discussion of this subject in more detail, but it will be clear that averaging of a significant number of measurements of the same journey (that is, distance) would have been required to get anywhere close to the accuracy of portolan charts. At this point I must introduce an aspect of the history of mathematics that has simply been ignored until now. The calculation of the arithmetic mean of a series of measurements of the same variable with the intention of improving its accuracy was not known in the Middle Ages; it was not introduced into scientific practice until the end of the seventeenth century (Plackett 1958).

Figure 6: Composite of the rectified regional charts of the Dulcert portolan chart. (1339)

Accurate *direction* measurements from one coastal point to another constitute an entirely different problem. The only possible instrument for measuring such directions would have been the magnetic compass. For the last one and a half century it has been a matter of debate whether the magnetic compass, in a form that could have been used to obtain meaningful direction measurements, was introduced and saw widespread use in the Mediterranean maritime world early enough to have allowed collection of a large number of direction estimates covering the entire Mediterranean and Black Sea. A simpler form of compass, consisting of a magnetised needle kept afloat in a bowl of water by placing it in a lengthwise-split reed or sticking it through a piece of cork, had been used for a long time to provide some directional help to mariners when the sky was overcast. In medieval documents this is referred to as 'the needle' ('acus'). Later the needle was placed on a spindle so that it could pivot freely and placed in a wooden box on which a compass card with thirty-two (or fewer) ‘wind’ directions engraved. Presumably later still the compass card was attached to the needle so that both could rotate freely. The latter innovation concerns the development of the mariner’s compass. The resulting compass was treated as a unit and indicated with the term ‘bussola’ (‘little box’). Only such a compass would in principle have been suitable to measure course directions. The transition of the name from ‘acus’ to ‘bussola’ is widely accepted as indicating the development stage of the compass as a single unit in the maritime world. Most researchers simply ignore the vital question of whether the magnetic compass was introduced in time to have contributed to the development of the portolan chart, but the first use of the of the term ‘bussola’ in a medieval notarial document has been shown to occur in 1349 (Pujades, 2007). The conclusion must therefore be that the charts were most probably already in existence before the mariner’s compass became firmly established in the maritime community.

5. THE ‘ACCIDENTAL’ MAP PROJECTION

The information presented above provides enough justification to doubt that portolan charts are original medieval creations. An additional argument concerns the map projection, on which near consensus exists that it is just an accidental by-product of the plane charting technique. To a geodesist/surveyor such as myself that does not make sense and I felt compelled to investigate that. The assumption that underlies the construction of portolan charts is that a control network of navigation data (magnetic bearing and estimated distance), built up from a large number of routes, formed the mathematical framework from which these charts were drawn. That is familiar ground for geodesists, because, prior to the mapping of large areas in modern times, a geodetic control network is measured. National triangulation networks have been established in the course of time for that purpose. However, this process only began in the eighteenth century, when four successive generations of the Cassini family succeeded in constructing the first topographical map (of France) based on a carefully measured geodetic control network. Positing a thirteenth-century marine network of accurate magnetic bearings and distances between points along the coast that is almost as accurate as the outline of France on the Cassini map must assume a extremely precocious community of scientifically-oriented cartographers and mariners.

I created three networks, for the Western Mediterranean, the Eastern Mediterranean and the Black Sea respectively, taking into account trade routes and prevailing wind directions, because medieval ships could only sail with the wind blowing predominantly from behind.

The core of this network consists of a series of coastal points between headlands and coastal cities, but not longer than 100 km each (about one day’s sailing). I calculated the rhumb-line distance and the magnetic bearing for each route for the curved surface of the earth, using a paleomagnetic model to estimate the magnetic declination for the year 1250 (Korte et al. 2005). This provided a simulated set of marine measurements from which, according to the hypothesis, a portolan chart might have been drawn. What makes this dataset different from real medieval data is that these simulated measurements are free from random (stochastic) measurement errors.

A hypothetical medieval cartographer could have constructed his chart from this set of bearing and distance data in any of very large number of ways. It is impossible to test all, but it is possible to constrain the options to a limited number of realistic scenarios. I evaluated what I consider the most plausible scenario, assuming that our hypothetical cartographer would start in Genoa or Pisa and that he would begin by charting the coastline using the data of the relatively short coastal legs. He would have come across his first ‘loop misclosure’, finding two positions for Marsala, Sicily, 89 km apart. Data conflicts due to plane charting are always in east-west direction. We cannot know how the cartographer might have dealt with such a conflict, but my assumption is that he would have adjusted a section of the North African coastline from, for example, Algiers to Cap Bon by compressing it to eliminate the data conflict. Adjustment of a section of coastline was a cartographic technique that was well-understood by portolan chart makers. The section prior to adjustment is shown in grey in figure 7.

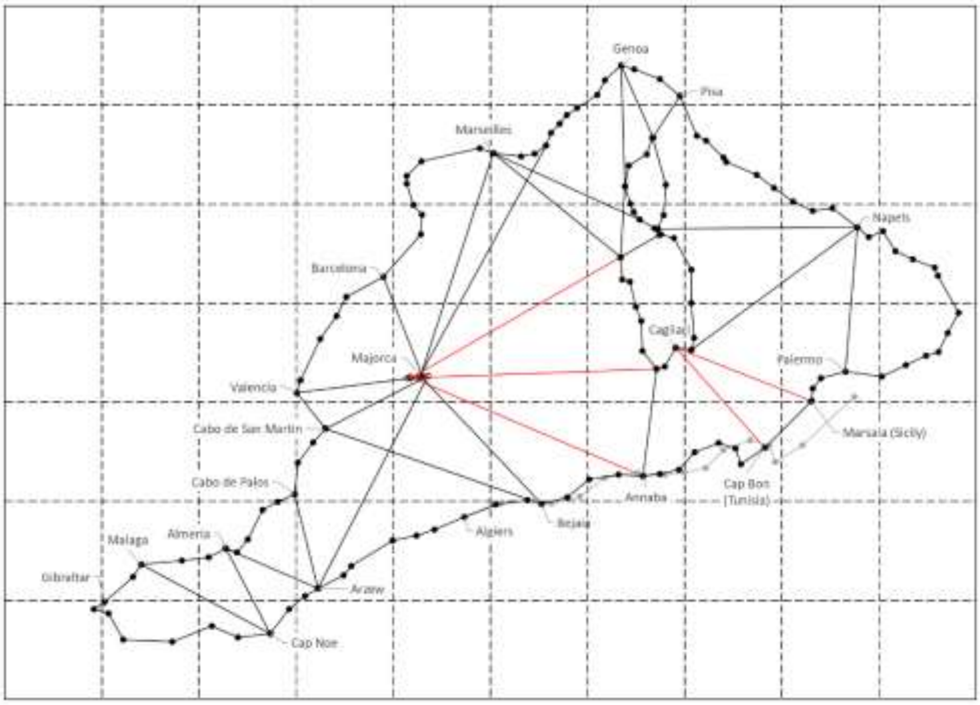

Figure 7: Conjectural plane-charted geodetic network in the western Mediterranean, hypothetically underlying the construction of a portolan chart. The grid interval is 200 km.

Chart making in the medieval Mediterranean was conducted by small commercial enterprises, often within a family, and it would be in the cartographer’s interest to avoid making unnecessary, small changes to the entire chart. I used a threshold value of 15 km for data conflicts. Assuming that Corsica and Sardinia would have been charted from the Italian coast and Majorca from the Spanish, most contradictions are small, with the exception of the long east-west courses to Majorca. In figure 7 the red lines indicate misclosures greater than 15 km than cannot be reduced further by shifting locations of points without unacceptably increasing the misclosures in other network points. It has to be borne in mind that the medieval cartographer would not have been able to separate the systematic errors due to plane charting and the random errors in the navigation measurements with which he is presumed to have been working. This iterative process yielded a set of simulated 'medieval' positions for all network points that would have formed the framework for further charting. The iterative computation of the networks for the eastern Mediterranean and the Black Sea networks yielded similar datasets. The key question is: to what extent does the shape of these networks agree with the correct modern network on a Mercator chart?

Geodetic network analysis is a specifically geodetic subject. How many measurements does one need and how accurate do these need to be to achieve a specified mapping objective? How does one find errors in the measurements? This is a specialism of the 'Delft School' of geodesy and is taught as part of the geodesy curriculum at the Delft University of Technology in The Netherlands. The approach I followed to find out whether the map projection of portolan charts is accidental or not makes use of the 'Delft School' methods of geodetic network analysis. The standard technique of identifying whether errors are present in the measurements of a geodetic control network is to use the sum of the squares of the measurement residuals from the least-squares computation (appropriately weighted), divided by the number of redundant measurements, as the test variable. This variable is called the *Mean Squared Error* (MSE) or sometimes *a posteriori variance*. If the value of the MSE agrees with expectations based on achievable measurement precision, then the conclusion will be that no gross errors were made in the measurements. However, if the MSE exceeds a tolerance value, the conclusion will be that one or more errors are present in the measurements. Further testing is then required identify the measurement(s) in error. One of the problems in geodetic surveying is that the size of any errors is rarely known; there is a reasonable chance of finding errors when they are large enough, but small errors will disappear in the measurement 'noise' and thus will never be found.

How does this principle apply to the case of the presumed medieval Mediterranean network? Correct processing of the hypothetical medieval network on the Mercator projection would require prior corrections to be applied to all measurements: the distances would have to be corrected by a scale factor deducible from the properties of the Mercator projection, and all compass bearings would have to be corrected for magnetic declination. But map projections and the phenomenon of magnetic declination were unknown in the Middle Ages, so no cartographer in the Middle Ages could have made these corrections. Thus, *each* measurement used in the medieval charting process would contain a known bias or gross error. Therefore, computing or drawing the network in the medieval way illustrated in figure 7 would lead to the data conflicts mentioned. Random measurement errors would have merged with the said biases. Imagining for a moment that real medieval measurements were available, subsequent fitting of the outcome of the medieval charting process to the Mercator projection would result in a MSE that would have two components, a *bias* and a *random* component. Each component would consist of the compounded biases and random errors in the measurements respectively. Separating the two is normally not possible. However, when the network is processed with all random measurement errors set to zero, the resulting MSE will consist of the bias component only. Let that bias component be called '*B*'.

Prevailing opinions in the history of cartography hold that this bias '*B*' must be negligibly small, because agreement with the Mercator projection is believed to be automatic. However, if the bias '*B*' is *not* negligibly small compared to chart accuracy, it will knock the bottom out of the hypothesis of a medieval origin of portolan charts, even without the arguments presented earlier in this paper. The following values for the bias in the MSE were computed for the three hypothetical marine networks.

$B_{Western\ Mediterranean} = 76.3\ km^2$
$B_{Eastern\ Mediterranean} = 98.2\ km^2$
$B_{Black\ Sea} = 41.1\ km^2$

It was established earlier that the mean accuracy of the regional charts of a portolan chart is 11.3 km. The biases computed for the three regional networks have to be normalized, that is, divided by, the square of this figure, 129 km^2, in order to be used in statistical testing.

When a gross error is made in a single measurement, for example a distance, which has a Normal or Gaussian error distribution, the random variations in measurement results do not disappear; measurement values simply continue to vary about the new, incorrect (theoretical) mean value.

In the case of the normalized MSE the error distribution is different – the normalized MSE is Fisher-distributed – but the idea is the same. With a Normal, Gaussian error distribution, negative values and positive values for errors have an equal chance of occurring, but negative values for the MSE are impossible; the MSE is the mean *squared* error, and squared numbers cannot be negative.

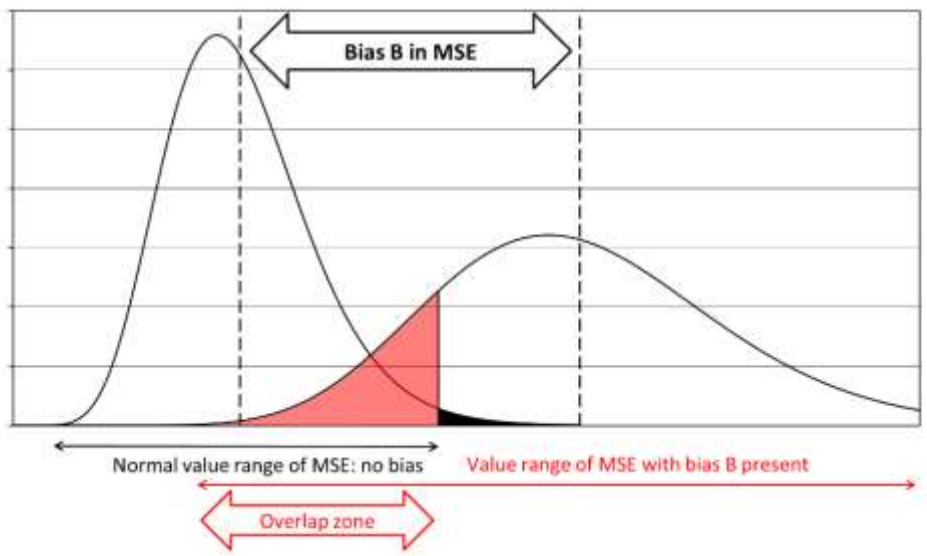

Figure 2 – Error distribution of the Mean Squared Error without a gross error (left) and with a gross error of magnitude 'B'.

In figure 9 the leftmost curve is the error distribution of the MSE of a (regional) portolan chart when the underlying marine network has been computed (or drawn) correctly, with appropriate corrections to all distances and all bearings, that is, no bias '*B*' is present. The righthand curve represents the error distribution of the MSE of a portolan chart when the underlying geodetic network has been computed or drawn, ignoring earth curvature effects and magnetic declination, that is, in the presence of a bias '*B*'. The black tail indicates the part of the lefthand curve that is no longer considered to reflect reality; the *area* of the red zone, belonging to the righthand curve, is the probability that the presence of bias '*B'* is not noticed. Translated to the portolan chart problem, the area of the red zone in figure 9 is the probability that it cannot be established whether the map projection is accidental or not; when the MSE value of a regional charts is in the overlap zone, it cannot be established whether the MSE belongs to the left-hand error distribution or the righthand one. Figure 10 shows the situation for the Western Mediterranean network 'to scale', based on the real value of the bias calculation.

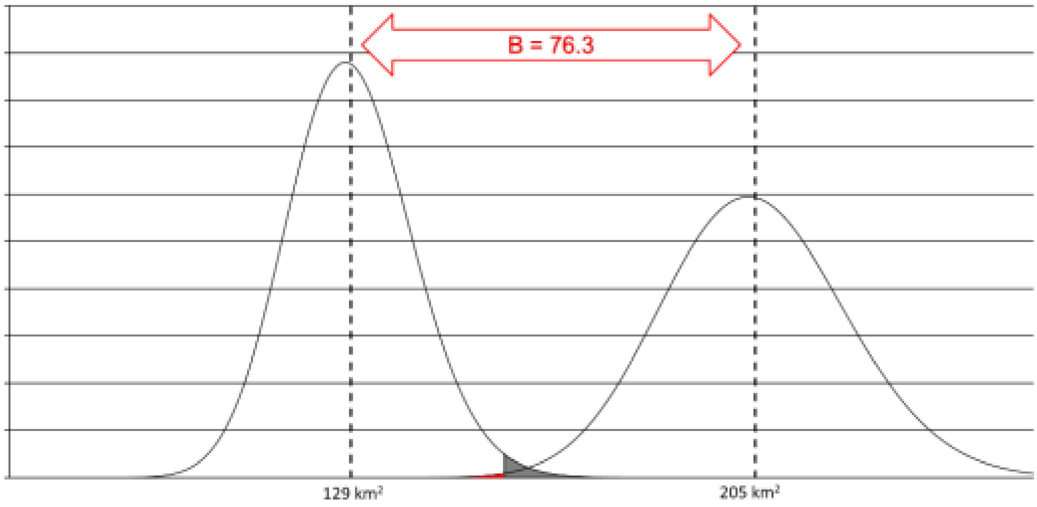

Figure 3 – MSE error distributions with mean values for marine geodetic network of the Western Mediterranean

The associated probabilities (P) of the map projection being accidental, computed for the three networks, is as follows.

Western Mediterranean: P = 0.0018
Eastern Mediterranean: P = 0.0000003
Black Sea: P = 0.31

The probability that the Mercator projection is coincidental in all three marine networks is the product of these three values and is negligibly small.

The caveat must be made that I have tested only a single charting solution. An alternative method of medieval charting than described above (see figure 7) might reduce the bias values slightly. The discrepancy between the spherical geometry of the earth and the Euclidean geometry of the map in each region remains the same and a different schemes of plane charting would redistribute the inevitable data conflicts in different, but similar ways. That would result in some variations in the bias values shown, but it is unlikely that these values would become so small that a coincidental Mercator projection would become a realistic possibility, given how small the total P-value is for the scenario evaluated, but, plausible though this may be, it is impossible to prove rigorously. Previously, I had calculated a least-squares solution for the plane charting of the three networks, following Woodward's suggestion described earlier in this article (Nicolai, 2016). Surprisingly, the bias (*B*) values for this solution were considerably larger.

A coincidental emergence of the Mercator projection would have to result from a fortuitous combination of random measurement errors and arbitrary plane charting corrections, such that the resulting residuals would mimic, to a sufficient extent, the magnetic declination in every compass bearing as well as the latitude-dependent Mercator distance magnification in every distance. This is highly unlikely.

6. ANALYSIS AND CONCLUSIONS

It appears that the source charts of the medieval portolan charts were a collection of separate regional charts, from which a mosaic was constructed by medieval Italian cartographers. These cartographers appear to have had only a vague notion of the exact scale an orientation of the source charts. The numeric analysis results suggest that the mosaic chart was created by overlaying and adjusting common sections of coast on adjacent regional charts. This accounts for the regional differences in scale and orientation in each chart.

The emergence of a Mercator or Mercator-like projection on medieval portolan charts as a coincidental by-product of a simple charting method that ignored earth curvature and magnetic declination is highly unlikely.

As a professional geodesist I am unable to suggest an alternative realistic mechanism that would accidentally generate the Mercator projection. I will therefore conclude that the map projection of portolan charts is most probably an intentional feature.

Rather than being simple, naive charts, as they are often described, portolan charts appear to be copies of sophisticated, accurate charts, intentionally drawn on the Mercator projection or a similar map projection. Surveying and constructing these source charts was well beyond the means and capabilities of medieval mariners and cartographers.

The intriguing question is: where do these charts come from if they are not medieval? This question cannot be answered, because the charts contain no clue that might direct researchers to the right answer. Considerably more, and possibly different, research will be required to answer this and related questions.

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BIOGRAPHICAL NOTES

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