Medieval Portolan Charts, a Geodetic and Historical Mystery

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Abstract

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 occurrences in the history of cartography. Using geodetic and statistical analysis techniques these charts are shown to be mosaics of partial 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 this map projection can only have been an intentional feature of the charts' construction. 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.

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 cartographic practices, 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 by historians, often made with a confidence that is unwarranted. Nevertheless, an admission was made in 1987 that we simply do not know how these charts were made and even who made them:

> "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".[1]

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 medieval origin of the charts. Understandably so, because the charts contain not a trace of a possible antique origin. The same is true of a possible Arabic-Islamic or a Byzantine origin. They share no characteristics with Ptolemaic maps and only a few Arabic-Islamic portolan charts, which appear to be copies of fifteenth century European charts, are extant. So, by a process of elimination, a European medieval origin is what remains. However, recent research has proven the consensus view incorrect.[2] 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 until now. 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. Additionally, the impact they had on later cartography is too clearly visible.

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. Their scale is approximately 1:5,500,000, that is, 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 between Cape Drâa or Cape Bojador in Morocco and 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 described above. 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, important names in red ink and the remainder in black.

Figure 1 – Portolan chart by Angelino Dulceti or Dulcert, (1339); image by courtesy of the Bibliotheque nationale de France.

A striking characteristic of these charts are 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*. This is created by interconnecting sixteen regularly spaced points on a circle, which covers the larger part of the chart.

The wind rose lines were colour-coded and named after the eight main ‘winds’ that the medieval sailor distinguished; the main winds are drawn in black, the eight so-called ‘half-winds’ in green and the sixteen ‘quarter winds’ in red. This results in a total of 32 directions, as shown in Figure 2. The intermediate ‘winds’ were indicated by names such as ‘between Greco and Levante’ and ‘a quarter wind from Greco to Levante’. The colour-coding would have facilitated the selection of the correct compass bearing when planning a voyage. The availability of the wind rose on the charts provides an absolute orientation of the charts and reveals that the entire coastline image is rotated anticlockwise by about 9°. This angle remains more or less constant until about 1600, when portolan charts oriented to true North begin to appear.

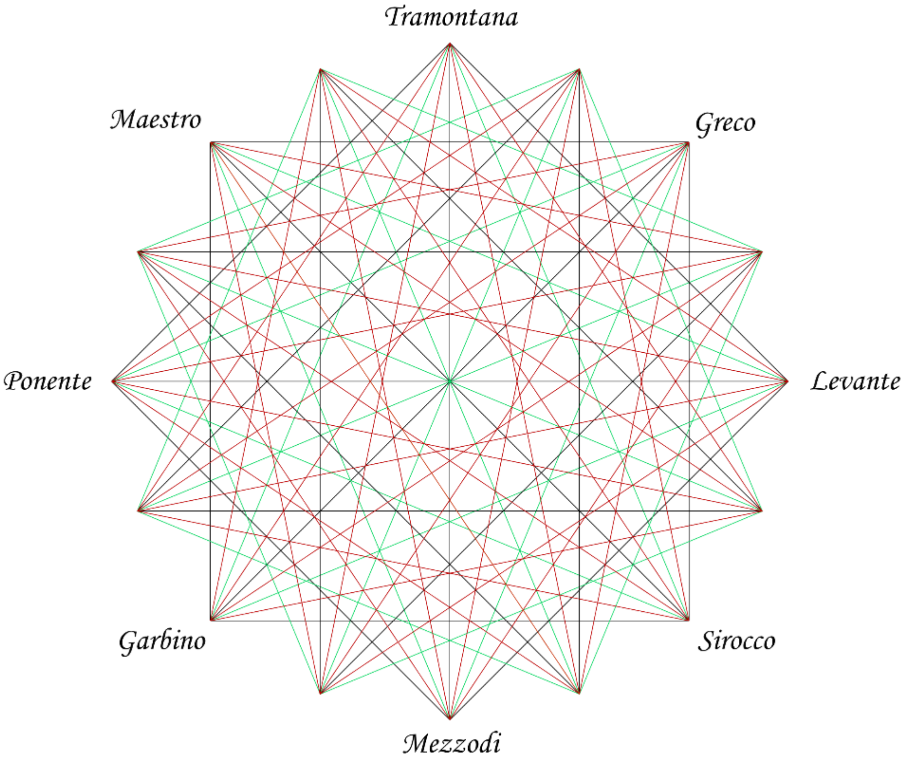

Figure 2 - Wind rose with the names of eight main 'winds'. Tramontana is North.

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 usage of portolan charts, presumably as a navigation aid.[3] 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 cartographic products are known that might have served as precursors or prototypes. 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 strange, 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 last quarter of the thirteenth century. 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.

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 (I am aware of only one dissenting voice). 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; only a small minority regards Greek-Roman antiquity as their origin.

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 consider the anticlockwise rotation of portolan charts as incontrovertible proof that the charts were drawn from magnetic compass measurements. 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.

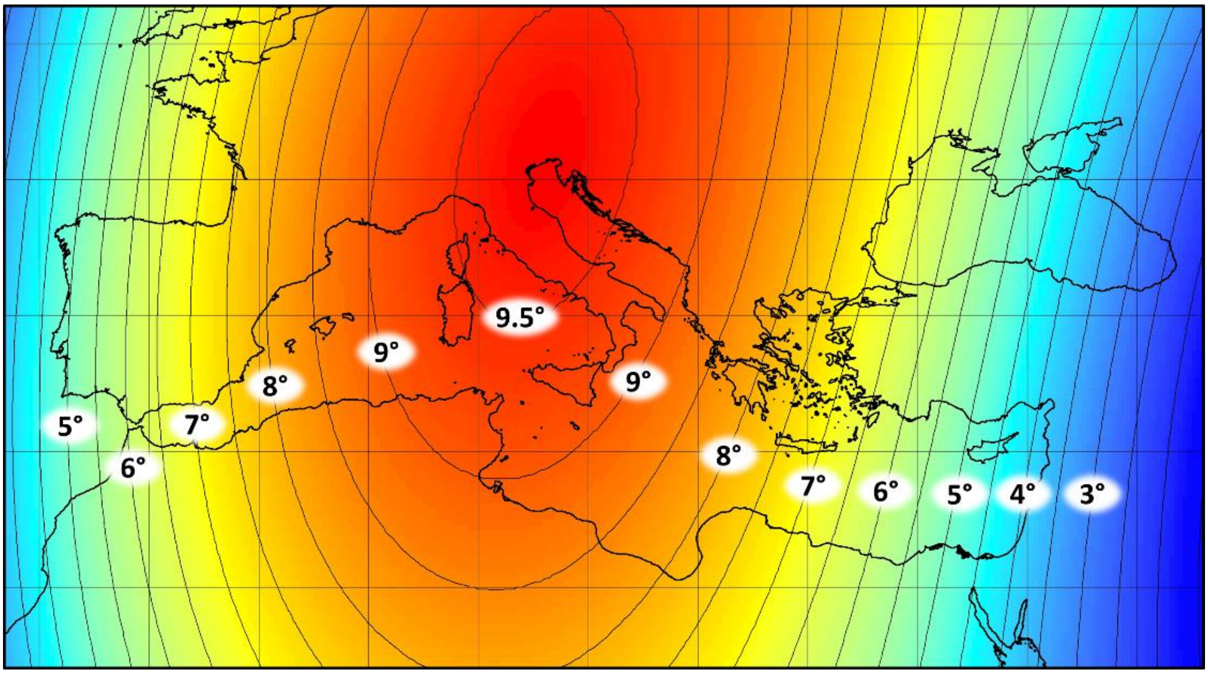

Figure 3- Magnetic declination from the model CALS7k.2 for the year 1250 (the positive values indicate an easterly magnetic declination)

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 perhaps 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 and some, including myself, deny that the charts were drawn from data collated in portolans.

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. Furthermore, it is assumed that some form of graphical 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'.

The historian of cartography David Woodward was courageous enough to be 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."[4]

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".[5] 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 agreement with the Mercator projection. As explained above, the consensus explanation of 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. The Mercator projection is almost unanimously considered to be an accidental by-product of the plane charting process by historians of cartography.

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 deviations 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.

Name	**Cartographer**	**Date of creation**	**Location**	**Catalogue Number**	**Identical points**
Carte Pisane	Anon. Genoese	End 13th c.	BnF, Cartes et Plans, Paris	Ge B 1118	444
Ricc 3827	Anon. Genoese	1300-1325	Bib. Riccardiana, Florence	3827	1015
Dalorto 1325	Angelo Dalorto	1325	Private collection	--	1130
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	G5672.M4P5 13	742
Roselli 1466	Petrus Roselli	1466	James Ford Bell Library, Minneapolis	bell001281466 mRo	860

Table 1 - Six portolan charts analysed

Many researchers have performed numerical ('cartometric') 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*, i.e. 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; on average a RMSE of 10-12 km was computed (figure 4); this equates to about 2 mm on the Dulcert portolan chart;
- there are differences in scale an orientation between the regional charts (figures 5 and 6);
- the boundaries between the coherent subsets of points did not align with the boundaries between the sub-basins of the Mediterranean (figure 7);
- 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.

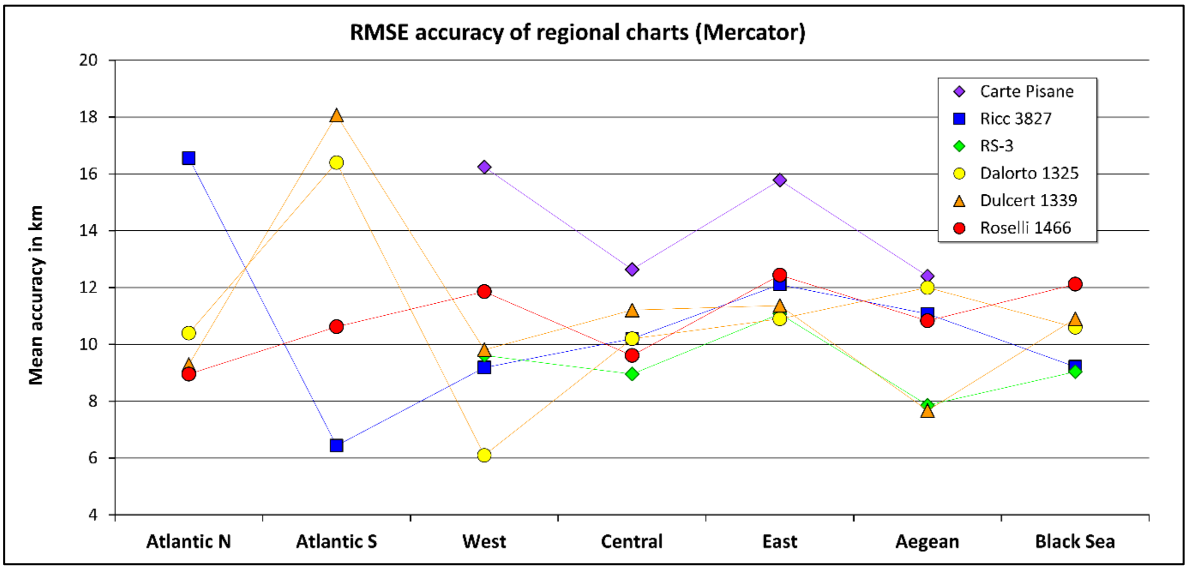

Figure 4 - Mean accuracies per sub-chart for the six charts analysed

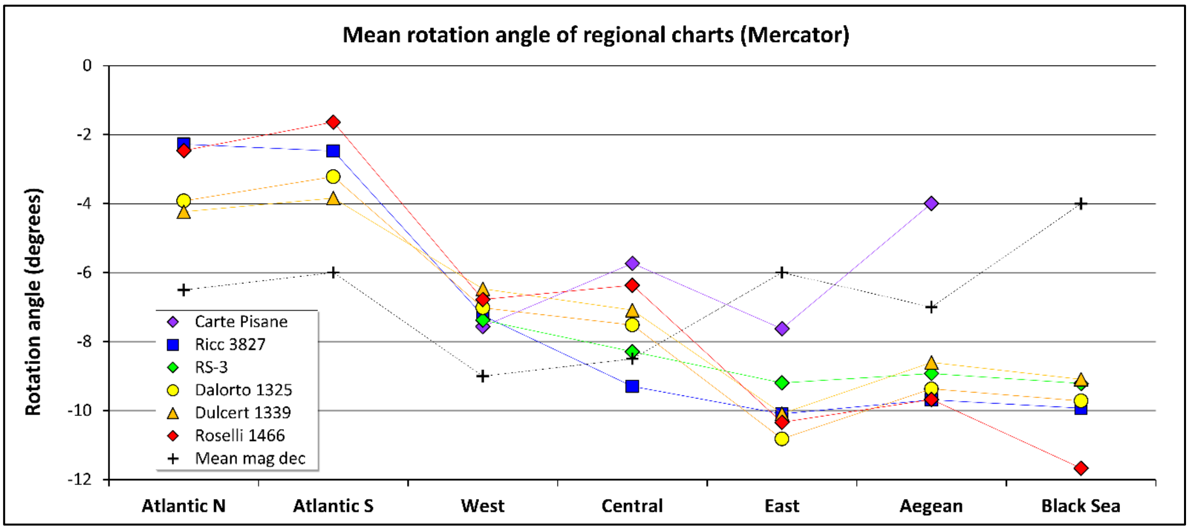

Figure 5 - Mean rotation angle per sub-chart of the six charts analysed

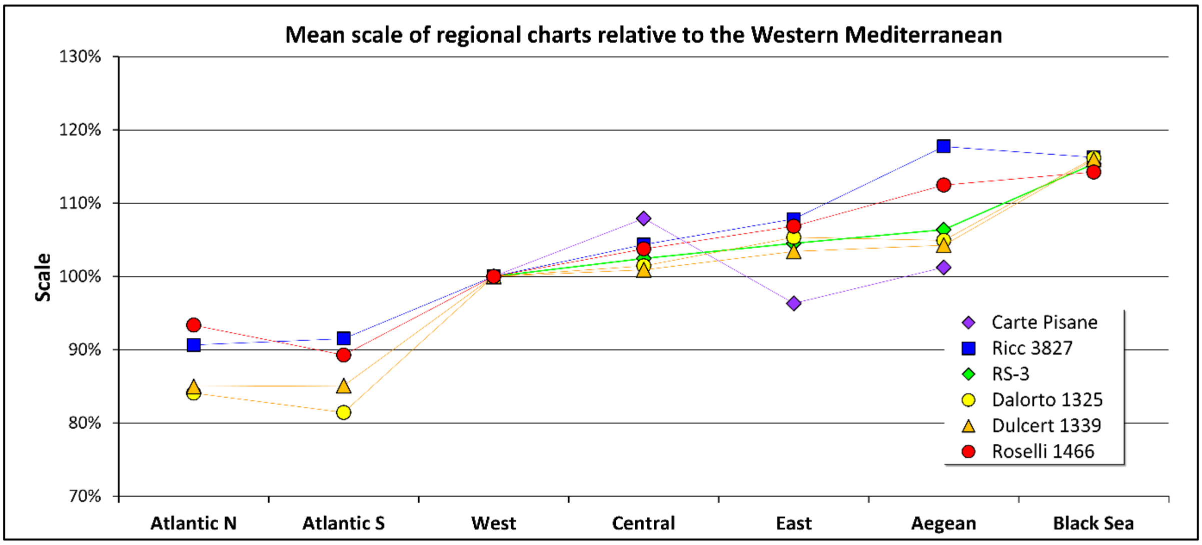

Figure 6 - Mean scale per sub-chart of the six charts analysed

The assumption of most researchers 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 objectively until the last quarter of the sixteenth century. Only subjective methods of estimating speed could have been used in the thirteenth century. The method of measuring the ship's speed that is usually assumed is that a wood chip was thrown in 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 estimate such short time intervals (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. It will be clear that, apart from limited accuracy of the resulting speed estimate, it would have involved enormous extrapolation to convert this to a distance estimate for the whole journey. And how accurate can one estimate time in this way? 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, one cannot estimate distance in this way better than about one third of the distance travelled (95% confidence level). 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 (i.e. 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.[6]

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 in the Mediterranean 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 made to float in a bowl of water by sticking it through a piece of straw or 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 the thirty-two 'wind' directions was 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 adoption of the compass as a single unit in the maritime world. Most researchers simply ignore the vital question whether the magnetic compass was introduced in time to have contributed to the development of the portolan chart, but in 2007 a researcher showed that the first use of the of the term 'bussola' in a medieval notarial document occurs in 1349.[7] Before him it had been shown that the description of the compass in literature shows a transition "well into the fourteenth century".[8] The conclusion must therefore be that the charts were already in existence before the mariner's compass became firmly established in the maritime community.

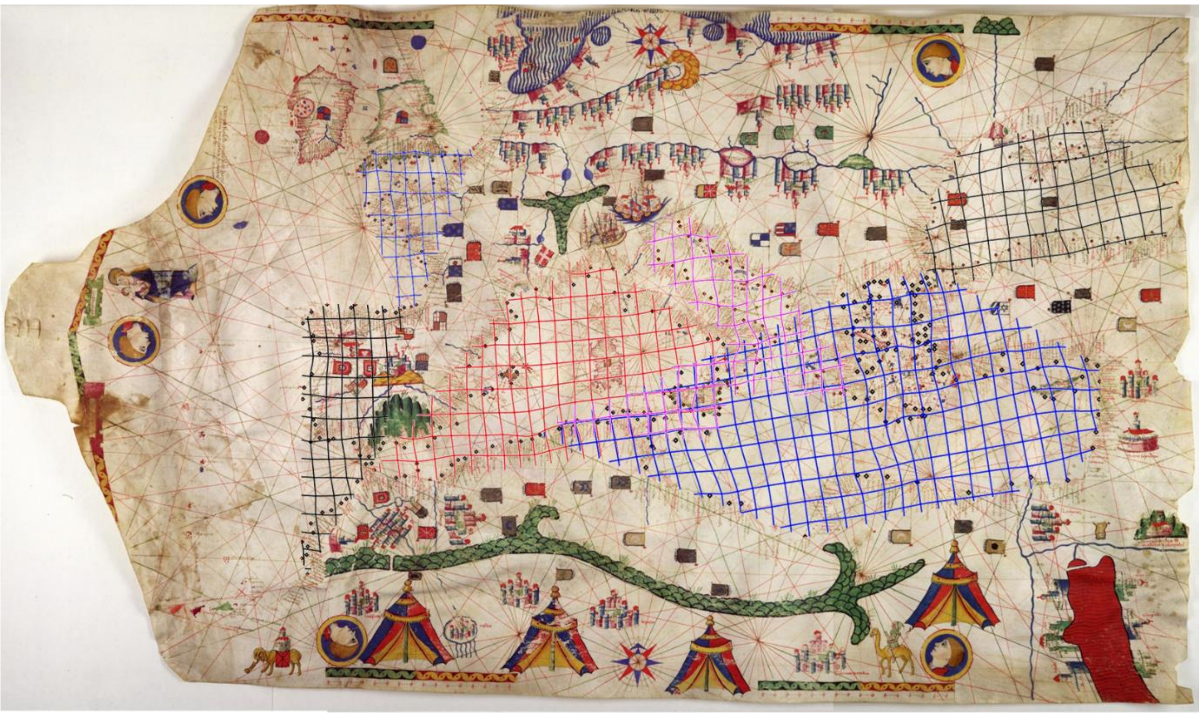

Figure 7 – Interpolated graticules per regional chart for the portolan chart of Petrus Roselli (1466). Identical points are shown as black dots. The graticules were generated using the program MapAnalyst. Image: by courtesy of the James Ford Bell Library, Minneapolis MN, USA.

THE 'ACCIDENTAL' MAP PROJECTION

The information presented above already provides enough justification for the conclusion that portolan charts cannot be original medieval creations. An additional argument concerns the map projection, which most historians of cartography believe 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 network of navigation data (magnetic bearing and estimated distance) built up from a large number of routes formed the mathematical framework on 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 needs to be established. 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 magnetic bearings and distances between points along the coast must assume a very precocious community of scientifically-oriented cartographers and mariners.

I created three networks for the Western Mediterranean, the Eastern Mediterranean and the Black Sea respectively, based on trade routes and prevailing wind directions, as medieval ships could only sail with the wind blowing predominantly from behind. The core of this network consists of a series of coastal points approximately 100 km apart (about one days' sailing for a medieval ship). 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.[9] 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, or stochastic, measurement errors.

Next, I computed the coordinates of the points in each network from this bearing and distance data, ignoring, as a medieval cartographer would have done, the curvature of the earth and the deviations due to magnetic declination that affect the bearing data. This approximates how an imaginary medieval cartographer would have approached the problem, be it that I used a computer and computed the coordinates by least-squares estimation, while a medieval cartographer could only have resolved the inevitable geometrical contradictions in the data graphically. Making a map or chart from the results of this exercise would be a matter of 'joining the dots' and filling in local details. Let us call this hypothetical medieval geodetic network a 'synthetic portolan chart'.

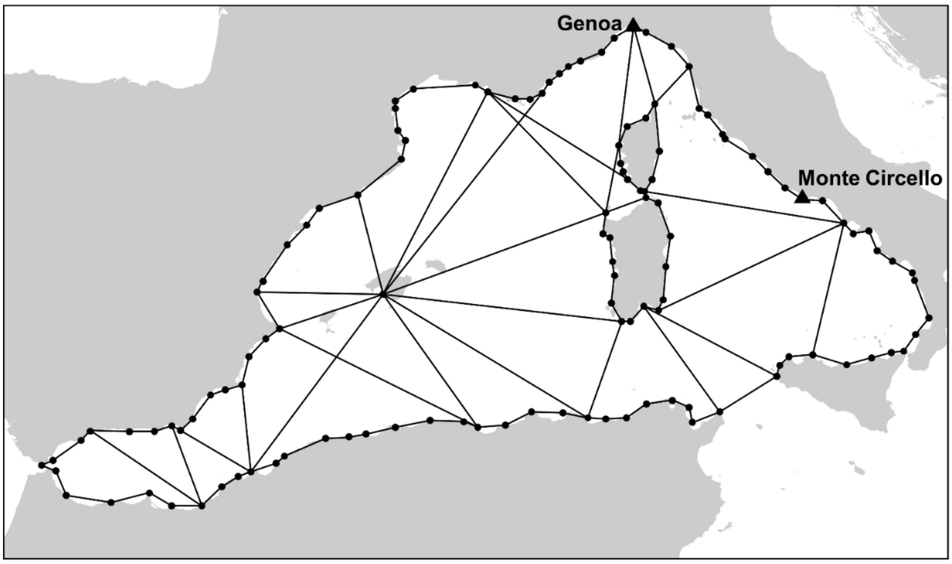

Figure 8 – The hypothetical medieval marine network of the Western Mediterranean

Analysis of a geodetic network is a typically geodetic problem. 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 may be 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 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, or MSE for shorty. 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 that is in error. If an error in one of the measurements is not removed or corrected, the shape of the geodetic network will be distorted, mainly in the vicinity of the location of the error. One of the problems in geodetic surveying is that we rarely know the size of any errors; we have a reasonable chance of finding errors, as long as they are large enough, but small errors will disappear in the measurement ‘noise’ and thus never be found.

How does one use this principle in the case of the presumed medieval Mediterranean network? Geodetically correct processing of the hypothetical medieval network on the Mercator projection would require corrections to be applied to all simulated 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. Carrying out a least-squares computation using the measurements thus corrected would evidently result in the same coordinates we started with. The fit would be perfect and the sum of the squared residuals, or MSE, would equal zero, because the simulated measurements contain no stochastic (or random) errors.

However, when those corrections are not applied, *all* measurements will contain a gross error and, in this case, contrary to the normal situation in geodetic surveying, we do know the magnitude of all errors. Carrying out least-squares computation of the coordinates of the point coordinates in the network will redistribute the errors over all points. The MSE will be biased by an amount we shall call ‘B’ and the good news is that we can compute ‘B’ exactly. In a *real* medieval marine network, it would be impossible to separate systematic errors from random measurement errors, but in our synthetic network there are no random measurement errors and, consequently, the MSE will be equal to the bias ‘B’.

Prevailing opinions in the history of cartography hold that this bias ‘B’ is negligibly small compared to the accuracy of portolan charts, expressed in the RMSE of 11 km. Since we have to compare squares, we need to square this baseline value to and MSE of 121 km (the ‘R’, designating the square root of the value, is gone now). Before my study of portolan charts no one had checked whether that assumption was actually correct. It was considered to be a self-evident fact. After all, map projections were unknown in the Middle Ages and so was the phenomenon of magnetic declination, so no cartographer in the Middle Ages could have made these corrections. 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.

Western Mediterranean: B = 100 km^2
Eastern Mediterranean: B = 255 km^2
Black Sea: B = 39 km^2

The MSE of the coordinate residuals caused by random (stochastic) measurement errors would have to be added to these figures to produce the MSE of 121 km^2 calculated for the portolan charts and it is clear that this will not work, because these values for ‘B’ are not ‘negligibly small’.

For the eastern Mediterranean the contribution of plane charting alone is larger than the entire accuracy of the real portolan charts. For the western Mediterranean, hardly any room is left for a realistic estimate of the effects of random measurement errors in vessel navigation. Although the magnitude of the figures of the bias in the MSE is clearly much, much larger than what is claimed, one cannot simply subtract the bias from the MSE value of 121 km^2. The latter value is the *mean* value of portolan chart accuracy. In reality variations about this mean value occur; there will be more accurate and less accurate examples of portolan charts. Due to this variation the problem should be approached by statistical testing, rather than looking at it as a simple addition or subtraction issue.

When a gross error is made in a single measurement, e.g. a distance, the random variation in measurement results does not disappear; it simply continues to vary about the new, incorrect mean (figure 9).

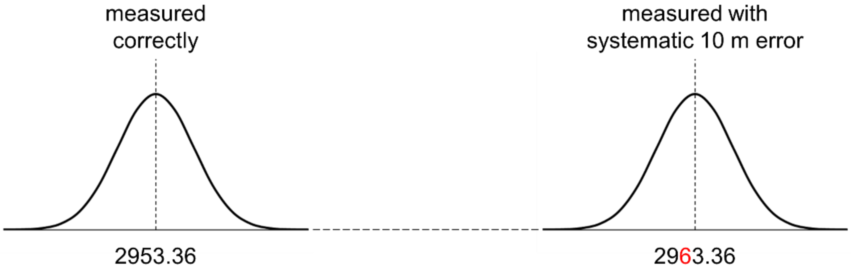

Figure 9 – Hypothetical distance measurement without (left) and with a gross error of 10 m (right). The random measurement error (Gaussian distributed) varies about the incorrect mean when a gross error is made.

In the case of the MSE values the error distributions are different, but the idea is the same. With a normal, Gaussian error distribution, negative values and positive values for errors have an equal chance of happening, but negative values for the MSE are impossible. The MSE is the mean *squared* error, and squared numbers cannot be negative. The error distribution of the MSE is therefore different.

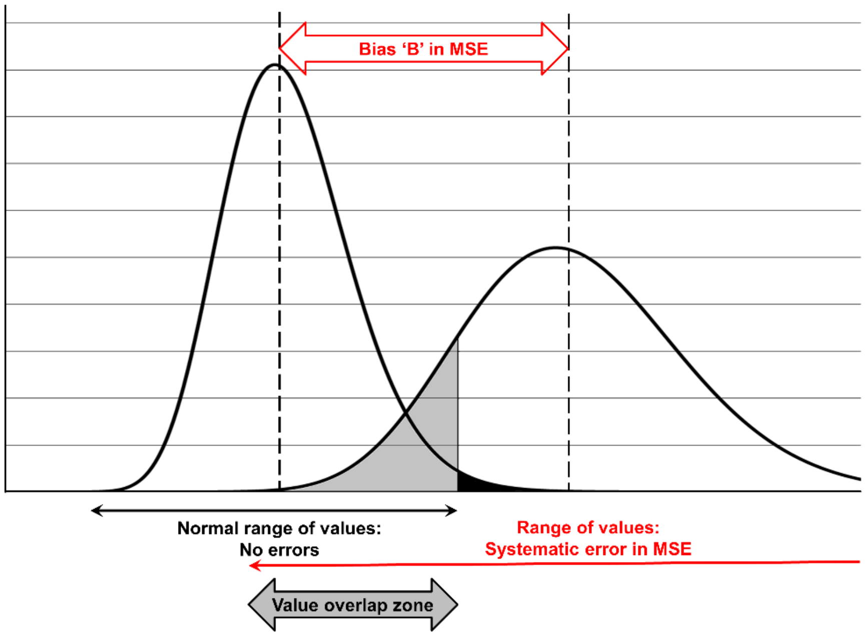

Figure 10 – Error distribution of the Mean Squared Error without a gross error (left) and with a gross error of magnitude 'B'.

In figure 10 the leftmost curve is the error distribution of the MSE of a portolan chart when the geodetic network that supposedly underlies it has been computed (or drawn) correctly, with appropriate corrections to all distances and all bearings. The righthand curve represents the error distribution of the MSE of a portolan chart when the underlying geodetic network has been computed or drawn while ignoring earth curvature effects and magnetic declination. The black zone indicates the part of the leftmost curve that is no longer considered to reflect reality.

Potential problems arise when the gross error or bias in the MSE is not large enough to create a clear separation between the value ranges in the situations without and with a gross error in the MSE. In that case an overlap will exist between the two value ranges (the grey zone in figure 10). When the value of the MSE is in that overlap zone, it is impossible to say whether the MSE value belongs the error distribution without the error or with the error. Translated to our portolan chart problem, the grey overlap zone in Figure 10 would mean that it would be impossible to establish whether the map projection is accidental or not. So, with this statistical grounding the question posed above may be reformulated as: "Is the bias 'B' large enough to create separated value ranges (or a sufficiently small overlap zone), so we can discriminate whether the MSE values of around 121 km^2 that were calculated for the actual charts indeed belong to the lefthand error distribution, that is, proper corrections were made to the geodetic measurements, or whether they might also belong to the righthand distribution, which would mean that the map projection could be an artefact of the medieval way of treating the geodetic network.

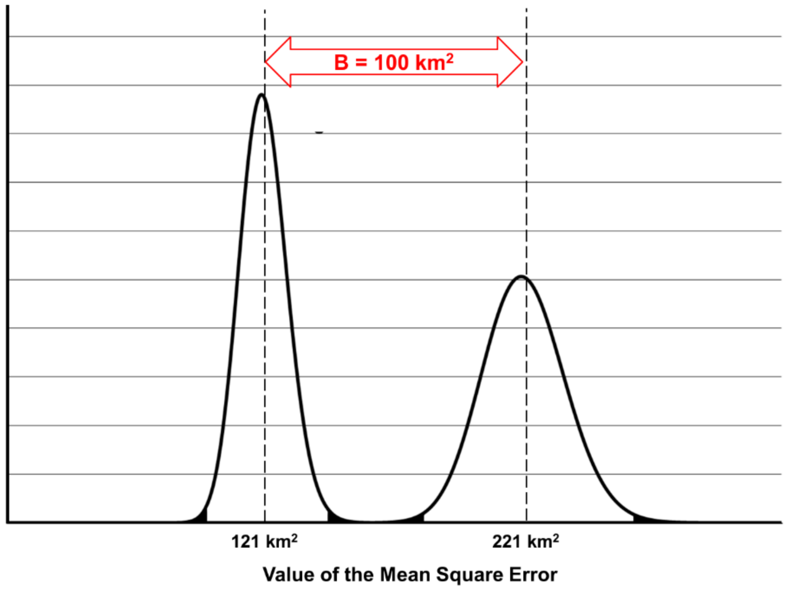

Figure 11 – MSE error distributions with mean values for marine geodetic network of the Western Mediterranean

Using the values for the bias ‘B’ given above, the error distribution curves for the Western Mediterranean geodetic network show a clear separation of the value ranges for the Mean Squared Error of the charts. The white zones in the middle part of each curve are the 99% confidence zones. For the Eastern Mediterranean the separation is even much larger, on account of the larger value for ‘B’. Only for the Black Sea network an overlap zone would exist, similar to what is shown in Figure 10.

The conclusion is therefore that the Mercator map projection cannot automatically emerge as an accidental by-product of a method based on plane charting and ignored magnetic declination. In the absence of any realistic alternative explanation the conclusion must be that portolan charts were designed to be drawn on the Mercator projection. This is one more powerful piece of evidence that portolan charts are pre-medieval.

ANALYSIS AND CONCLUSIONS

Rather than being simple, only *relatively* realistic charts, as they are often described, portolan charts are copies of sophisticated, accurate charts, intentionally drawn on the Mercator projection or a similar map projection. Surveying and constructing these source charts were well beyond the means of medieval mariners and cartographers.

It appears that the original portolan charts consisted of a collection of separate partial source charts, from which a mosaic was created by medieval Italian cartographers. These cartographers appear to have had only a vague notion of the real scale an orientation of the source charts. The overlaps of the subsets of identical points suggest that the mosaic chart was created by overlaying common sections of coast on the partial charts. This accounts for the regional differences in scale and orientation in each chart.

It has been possible to draw these conclusions by application of the same geodetic-probabilistic methods that are normally used for the detection of measurement errors. Incidentally, the same technique is also used in automatic face detection algorithms.

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 those questions.

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[4] Campbell 1987, 388. Campbell states that Woodward wrote the relevant section.

[5] Patrick Gautier Dalché, “Cartes marines, representation 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* (Rome: École française de Rome, 2001), 20.

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