WHOI-92-14

C. 1

Woods Hole Oceanographic Institution

WOODS HOLE OCEANOGRAPHIC INSTITUTION

1930

Numerical Simulations of Columbus' Atlantic Crossings

by

Roger A. Goldsmith and Philip L. Richardson

February 1992

Technical Report

Funding was provided by a grant from the Nova Albion Foundation and the Government of the Turks and Caicos Islands.

WHOI-92-14

Numerical Simulations of Columbus' Atlantic Crossings

by

Roger A. Goldsmith and Philip L. Richardson

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

February 1992

Technical Report

Funding was provided by a grant from the Nova Albion Foundation and the Government of the Turks and Caicos Islands.

Approved for Distribution:

Robert C. Groman

Robert C. Groman, Manager
Information Systems Center

Abstract

The transatlantic route of Columbus was simulated incorporating corrections for historical winds, currents and hypothetical magnetic variation in order to estimate where the first landfall occurred. Earlier simulations using an 1899 map by Van Bemmelen and assuming zero magnetic variation in the Bahamas produced a landfall near San Salvador (Watlings Island). New theories postulating a Geometric league of 2.67 nautical miles and a westerly magnetic variation of approximately one point (11.25°) for the western terminus result in a landfall near the Turks and Caicos Islands. A westerly variation of this magnitude in the Bahamas has been inferred from early charts — the islands are shown several degrees too far north, which would have occurred if early navigators had been set imperceptibly southward by westerly variation — by studies of directions within the islands, and by studies of early navigation books. The simulation of subsequent voyages by Columbus lend further weight to a westerly variation of about one point in the region of Bahamas. Our work shows that a Grand Turk landfall cannot be ruled out based on the transatlantic portion of the voyage as has been suggested in the past. A more accurate simulation of the voyage and first landfall requires a more accurate representation of the field of magnetic variation.

Table of Contents

List of Figures

List of Tables

1 Introduction

In a previous study we investigated Columbus's first transatlantic crossing with the intention of locating his first landfall (Goldsmith and Richardson, 1987; Richardson and Goldsmith, 1987). In that examination we introduced the technique of using climatological averages for wind and current in estimating the track made good. The poorly known field of magnetic variation for the year 1492 was found to be the dominant factor in determining the route Columbus would have taken and in the subsequent determination of his landfall. In comparison, corrections for wind and current were rather small; the latitudinal deflection by winds and currents in the eastern Atlantic half of the voyage was nearly cancelled by that in the western Atlantic.

In this study we examine more closely the field of magnetic variation and its impact on the first landfall. Specifically, we wish to determine if Grand Turk is a reasonable landfall based on recent reconstructions of the historical magnetic field. In our opinion both Grand Turk and Watling Island (San Salvador) match Columbus's description of the first island yet, a landfall in the region of the Turks and Caicos has been dismissed by many investigators as being too southernly and inconsistent with Columbus's use of the compass and the course he recorded in his log. Our conclusion is that Grand Turk is a reasonable landfall if the magnetic variation in the Bahamas was about one point westerly (11.25°W). We also seek whether various fields hypothesized can be used to adequately explain the subsequent transatlantic crossings of Columbus and investigate the effects of some recent findings in this area of research, notably the length of the league and the use of a precalibrated compass. In particular, the use of a Geometric league equaling 2.67 nautical miles was found to be consistent with a Grand Turk landfall.

In our earlier study we concluded that the endpoint of the best reconstructed cruise track indicated a landfall at Watling Island. This was based on the courses and distances given by Marden and Judge (Marden, 1986a), a seasonal wind and current field (see Appendix 2) made by averaging the fields for September and October, and the field of magnetic variation as proposed by Van Bemmelen (1899) for the year 1500 ad. Van Bemmelen's map delineated the magnetic variation only east of 60°W longitude. For consistency with the work of earlier investigators (Schott, 1881; McElroy, 1941; Marden, 1986b) we assumed there was nearly zero magnetic deflection for the Bahamas in the region of the landfall. This was found to be a critical assumption, started by investigators who favored a mid-Bahama landfall. Recently, it has been suggested that westerly variation of approximately one point existed in the Bahamas at the time of Columbus's first voyage (see Appendices 3 and 4) which implies that the earlier tracks based on the assumption of zero variation in the Bahamas could be considerably in error. We further assumed a league comprised of 2.819 nautical miles and used a leeway factor of 0.014. These values were based on the research of Marden (1986b) and Judge (1986) and were held constant so as to provide the comparison of the effects of different current and wind fields. Our best reconstructed track (case 0a) gave an estimated voyage termination at 23.766°N, 74.359°W, 24 kilometers south of Watling Island (Figure 1).

In all the simulations which follow we used rhumbline positioning with a 30 minute computation interval unless otherwise noted. All course values were rounded to the nearest tenth of a degree heading and tenth of a league distance travelled. A test on one of the transatlantic crossings showed that the rounding assumption moved the termination point only 0.6 kilometers. We also reconstructed Van Bemmelen's field of magnetic variation to include a wider latitudinal range. This new field (case 0b) did not significantly alter the termination point (23.745°N, 74.343°W), moving it only 2.8 kilometers to the southeast.

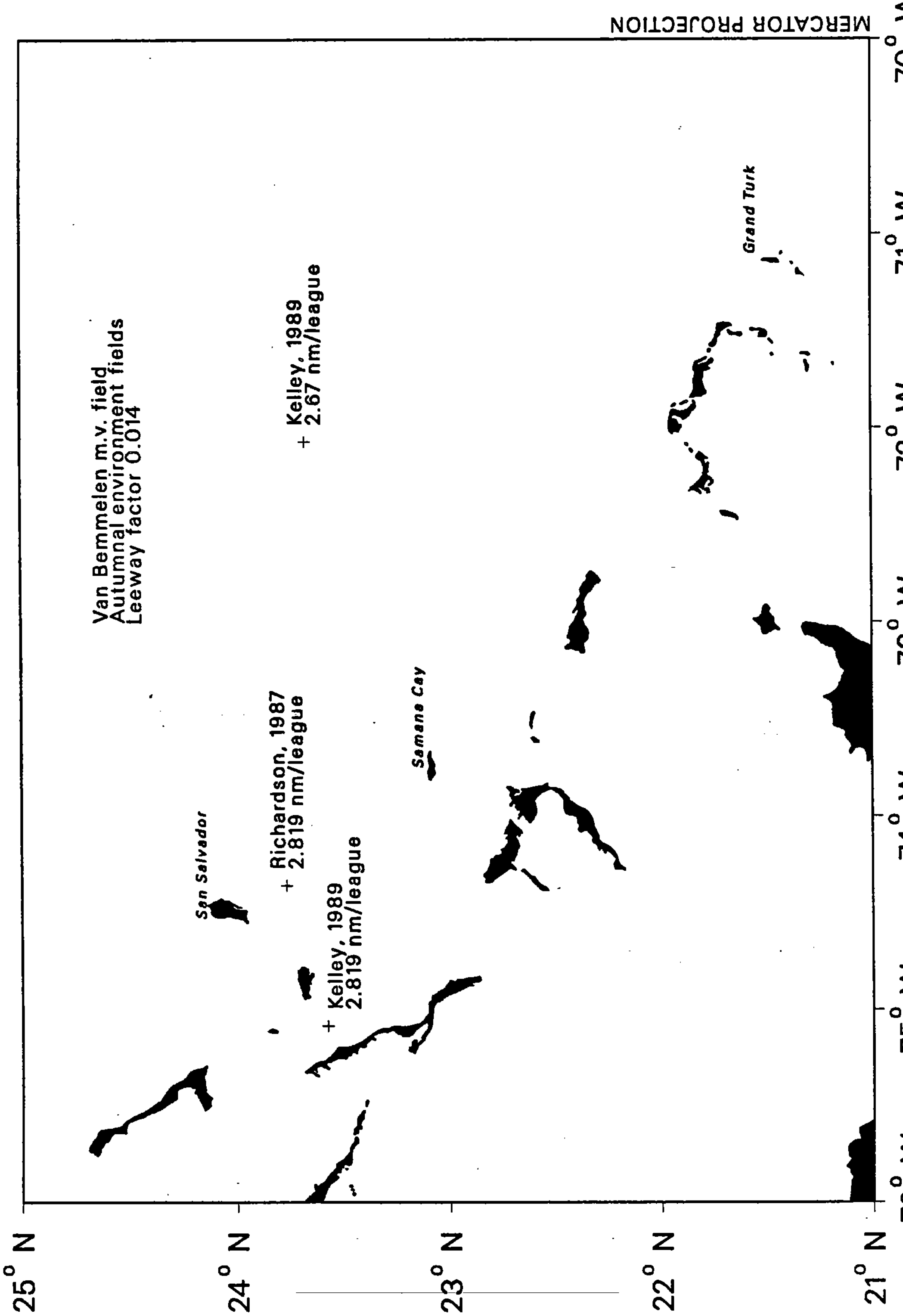

Figure 1: Updates for track and league.

2 Use of the Course Proposed by J. Kelley

In our original reconstruction of the outward voyage we used courses and distances (or, more simply, "course") based on those proposed by Marden and Judge to facilitate the comparison of their results and ours obtained using historical wind and current fields. In fact, the slightly different courses and distances proposed by several investigators (Goldsmith and Richardson, 1987; Kelley, 1989a; McElroy, 1941) did not produce any more variations than were caused by factors such as various current fields or leeway coefficients. Since our previous study, several authors have produced new translations of the Diario (Fuson, 1987; Dunn and Kelley, 1989), and for this study of the initial landfall we have adopted a course recently proposed by Kelley (1989a). This has new interpretations for the course on 09 September, the distance covered on 09 October, and the final hours just before landfall. As in our previous study we used the cruise starting point originally proposed by McElroy (1941).

The use of this new course results, quite naturally considering the adjustments made in interpretation, in a termination point about 70 kilometers to the westsouthwest of our earlier scenario. The computed coordinates (23.570°N, 74.978°W) represent a comparison for comparable time sailed. In fact, Kelley's interpretation adds an additional two hours to the end of the journey and results (case 1a) in a track termination at 23.575°N, 75.084°W, an additional 11 kilometers to the west (Figure 1).

3 The Conversion of Nautical Miles Per League

In addition to his course interpretation, Kelley (1983, 1987, 1988b) and others have also postulated the use by Columbus of a Geometric league equivalent to 2.67 nautical miles. Kelley suggests that Columbus used the Geometric league of

Mediterranean origin in his own estimates of speed and distance, but that he converted his values into Portuguese maritime leagues which his pilots were using. The Geometric league is 5/6 of the Portuguese maritime league as given by the ratio of values in Columbus' log. Using this new value of 2.67 nautical miles/league we computed a termination at 23.674°N, 72.074°W, well to the east and slightly north of the previous result obtained using the 2.819 nautical miles/league conversion factor (Figure 1). This endpoint leaves Columbus well out in the Atlantic, suggesting that either the Geometric league is too short or that the endpoint should be further south, in the vicinity of the Turks and Caicos islands.

4 Exploring the Field of Magnetic Variation

A method of inducing a more southerly track involves finding a field of magnetic variation which satisfies the requirements of making a landfall while other factors, such as vector average current and wind fields, leeway, league conversion and course, remain constant. To determine a new field we initially assumed that the magnetic variation was known at only two points, 3.0 °E variation in the Canaries (Schott, 1881), and an unknown variation at the site of a suspected landfall. A midpoint of the Caicos group (21.60°N, 71.80°W) was initially chosen as an arbitrary termination point in the nearest island group associated with a landfall when the estimated track length was computed using the Geometric league. It is important to note that with the above assumptions and with the proposed 2.67 nautical miles per league conversion factor, the Turks and Caicos group is the only realistic West Indies landfall possible. However, a lack of certainty in both the precise length of the league and in Columbus' estimates of distance and course prevent this from being the definitive conclusion. Values ranging from 10° to 20°W variation were assigned to this location and the resulting fields were generated. The algorithm used weighted observations with a quadratic interpolation and smoothing. By definition the resulting field is very smooth and it gives a good first estimate of the variation needed to achieve a landfall with the other factors held constant. The overall effect, shown in Figure 2, is to shift the endpoint south southeastward approximately 300 kilometers for a 15°W variation, illustrating the large effect of variation (cases 3a, b, c). Through an iterative process we determined that a 13.3°W variation produced conditions appropriate for a landfall in the Turks and Caicos islands (case 3d). The termination point (21.704°N, 71.282°W) lies roughly between Grand Turk Island and East Caicos Island. Grand Turk has a more favorable distance but lies slightly to the south of this termination; East Caicos lies approximately 30 kilometers to the west along the projected track. (A landfall close to Grand Turk was found to require a 13.5°W variation there.)

We took this last scenario (case 3d) as a base upon which we would incorporate additional information known about the compass variation. As contained in the Diario, Columbus observed three compass bearings of the polar star. To summarize, the observations are a variation of 0.0° on 13 September, 5.6°W (half point) on 17 September and 5.6°W on the 30th. By taking Columbus's position on the above dates, and using these three observations of the variation, we generated a new field. The effect of the new field was to produce a new track, and the new positions at the time of the star observations were used to update the field generation conditions. This was done iteratively until the changes between successive runs were less than a threshold criterion. The goal was not to identify an exact position for the landfall, but to arrive at a termination point in the vicinity of the Turks and Caicos while keeping the field of variation consistent with Columbus's observations along the track. The resulting field produces a track (case 3e) which has Columbus's observations within 2.0° of the field value and requires a westerly compass variation near 12.0°W at the mid Caicos (Figure 3). The variation at the termination point is 11.7°W. Suffice it to say there are many possible solutions to the problem of constructing a field necessary

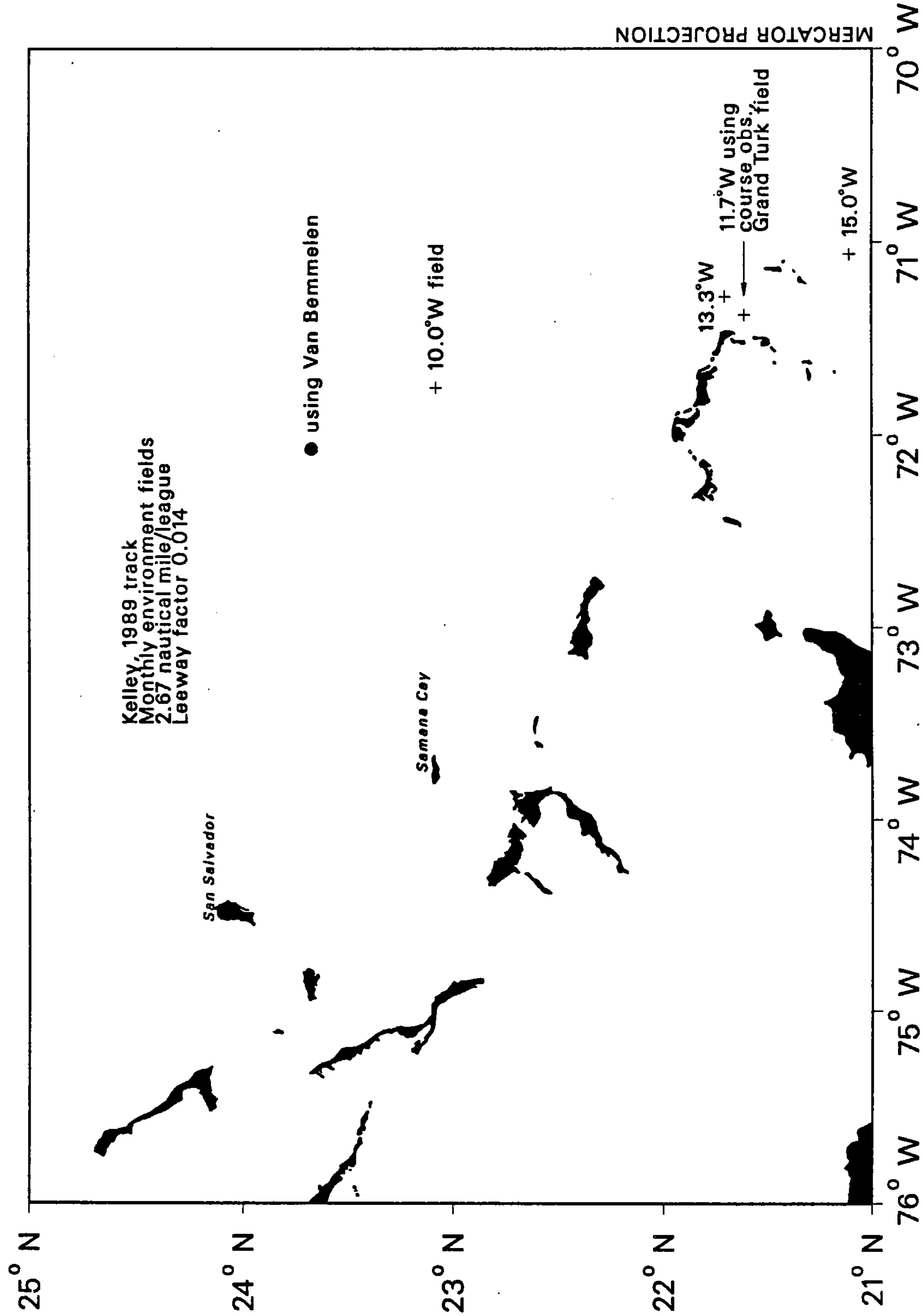

Figure 2: Effects of magnetic variation at the Caicos.

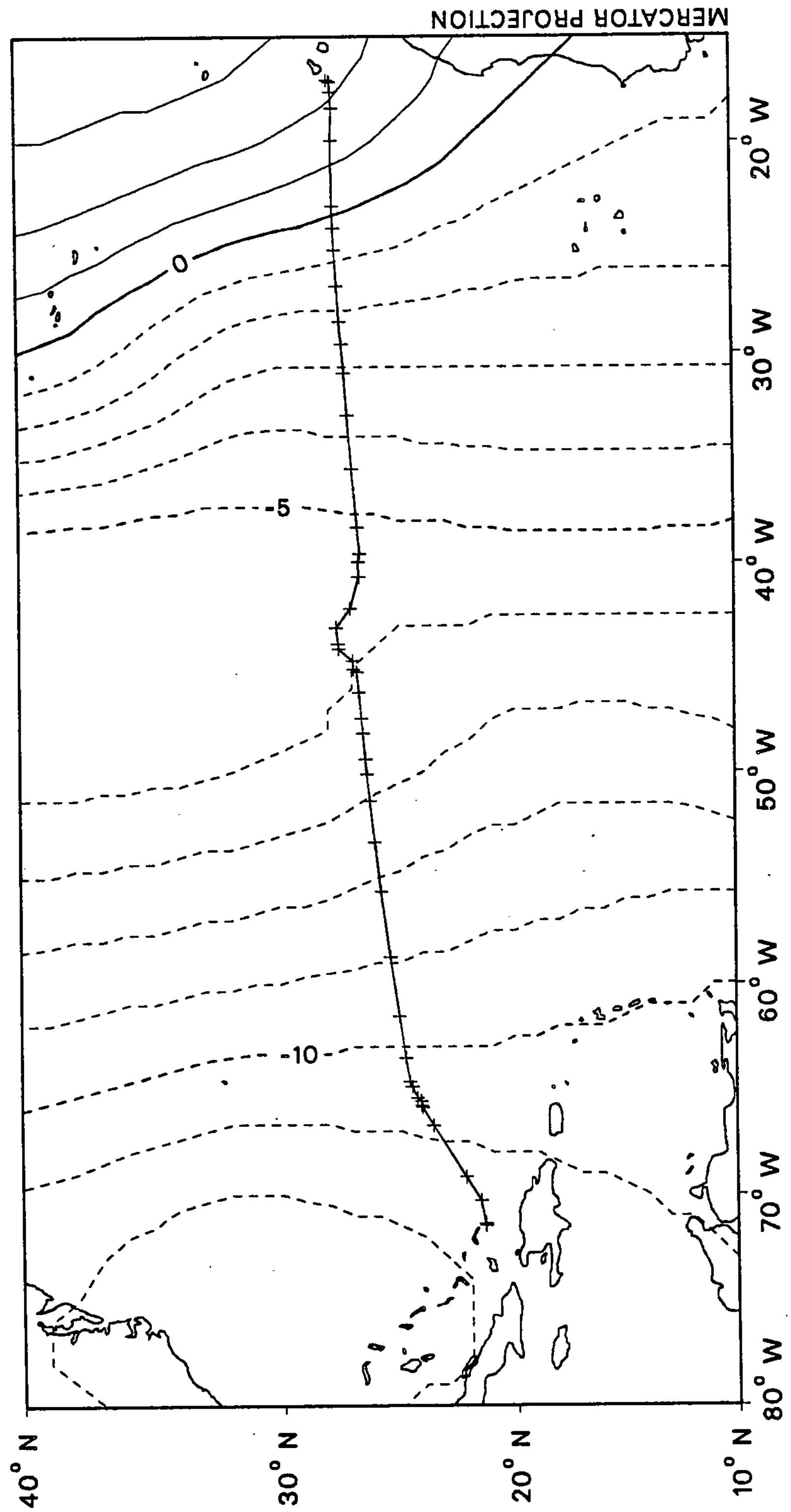

Figure 3: Magnetic variation (degrees) for Grand Turk landfall. Dashed line indicates westerly deflection.

to force the track endpoint near land. This is merely one that is at least internally consistent and not unreasonable. It suggests that a westerly magnetic variation of around one point deflects the transatlantic track southward so that the endpoint lies near Grand Turk.

5 The Use of a Precalibrated Compass

We should note the possibility that Columbus's track could also have been set southward to Grand Turk if he used a compass precalibrated to read true north at Seville, which had around a 6°E variation. Marvel (personal communication) has found evidence that Columbus could have used a precalibrated compass on his first voyage. Whether or not Columbus's compass was precalibrated is not important in our simulation as long as Columbus used the same compass both to steer by and to observe the local magnetic variation (as he recorded three times). This is because we used Columbus's observations of magnetic variation to correct his course and his observations of the polar star would have included both local magnetic variation and any precalibration. However, if his compass was precalibrated by 6°, then our inferred westerly magnetic variation in the vicinity of the landfall needs to be lowered by 6°. We think it is unlikely that Columbus used a precalibrated compass because he emphasized his observations of the agonic line lying near the Azores on 13 September. If he had used a precalibrated compass the apparent agonic line would have been located at Seville, not near the Azores.

We also tested a field of magnetic variation proposed by Marvel (1988) and shown in Figure 4. The result (case 2a) was a southward deflection of the track to a termination point of 22.408°N, 71.293°W, well short of the nearest land. Mayaguana Island lies along an extension of the westward track. The Turks and Caicos lie at approximately the correct distance but require a more southerly track. With the

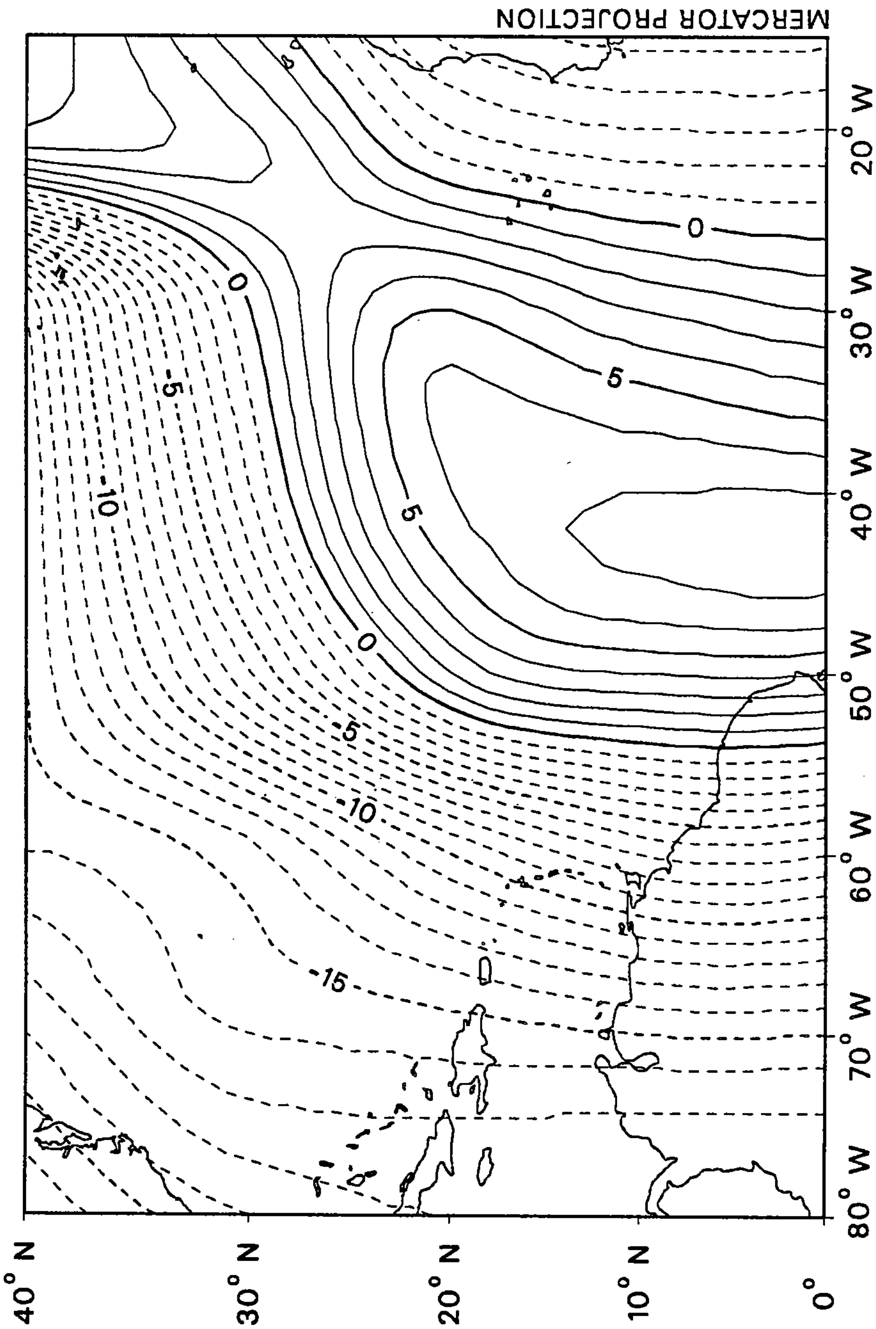

Figure 4: Magnetic variation (degrees), from Marvel (1988). Dashed line indicates westerly deflection.

assumption that the distance was correct for a landfall at Grand Turk Island, we looked for the additional compass offset or calibration needed to arrive at Grand Turk using the magnetic field proposed by Marvel. A few iterations converged on a value of 1.8°W offset (case 2b).

6 Variation of Wind and Current Fields

Our original analysis used a vector average field of wind and current taken from the individual monthly fields (see Appendix 2). We illustrated the effect of using the various monthly component fields and observed the resulting track terminations to range over an area 20 by 30 kilometers. In our present analysis we again examined the effect of using the combinations of monthly fields (cases 5a, b, c, Figure 5). Here the spread is slightly larger in the north–south direction, covering a distance of about 60 kilometers between the two extremes. As before, the date-determined monthly fields deflect the track to the southwest while the strong circulation of a September field used for the whole voyage deflects it to the north. We have chosen to use the monthly fields in subsequent processing, primarily to simplify the bookkeeping and processing operations associated with the larger number of fields and greater area of study.

7 Effects of Leeway

Our previous study also illustrated the effect of varying the leeway factor and this analysis is repeated here (cases 6a, b, c, d, e). The termination points range from 21.551°N, 71.422°W in the north, assuming no leeway correction, to 21.281°N, 71.470°W at the southern extremity when a leeway factor of 0.020 is used (Figure 6). This represents a range of about 30 kilometers in a north to south line, consistent with the ships predominantly westward track. Compared to the results obtained for a

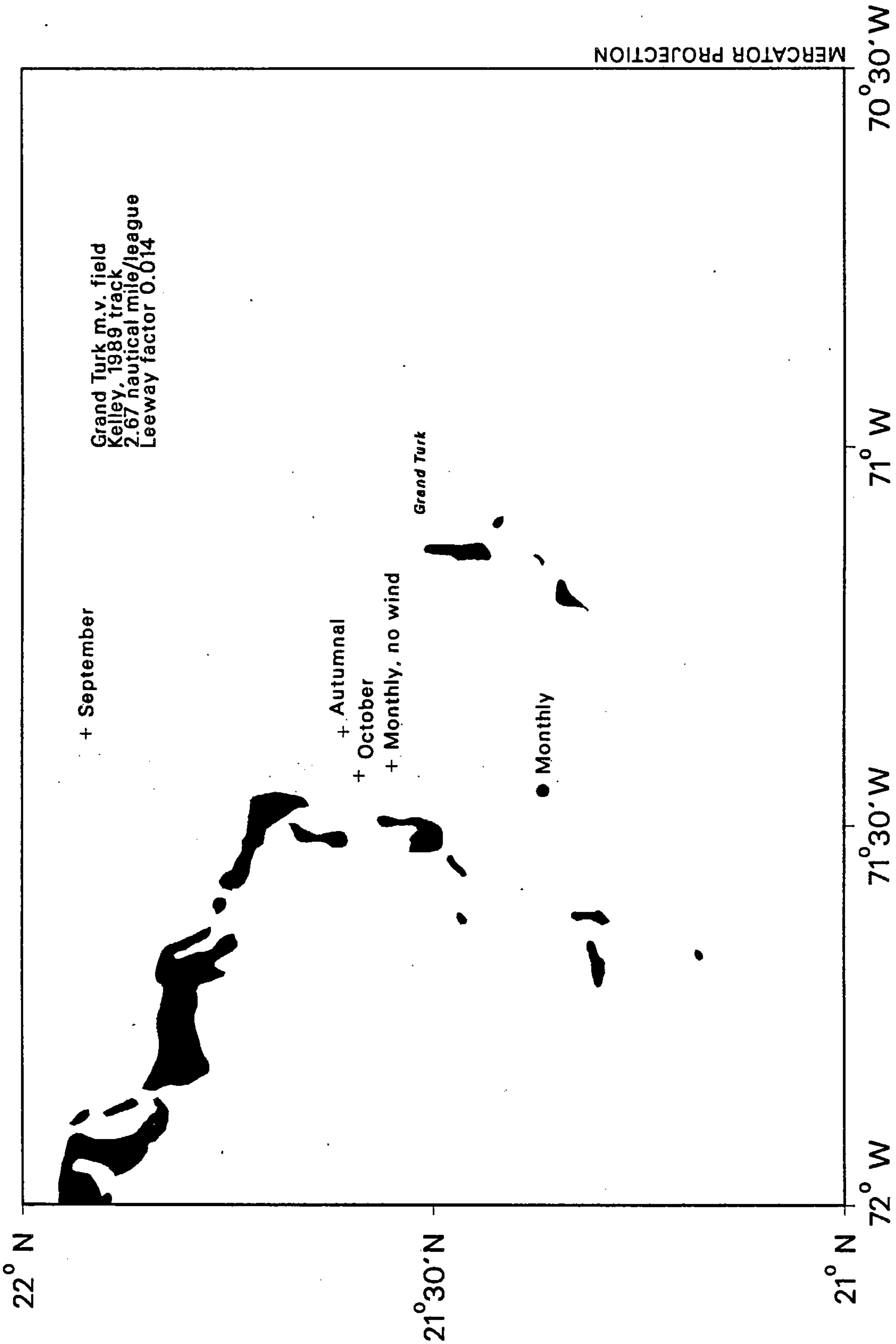

Figure 5: Effects of environment (Grand Turk field).

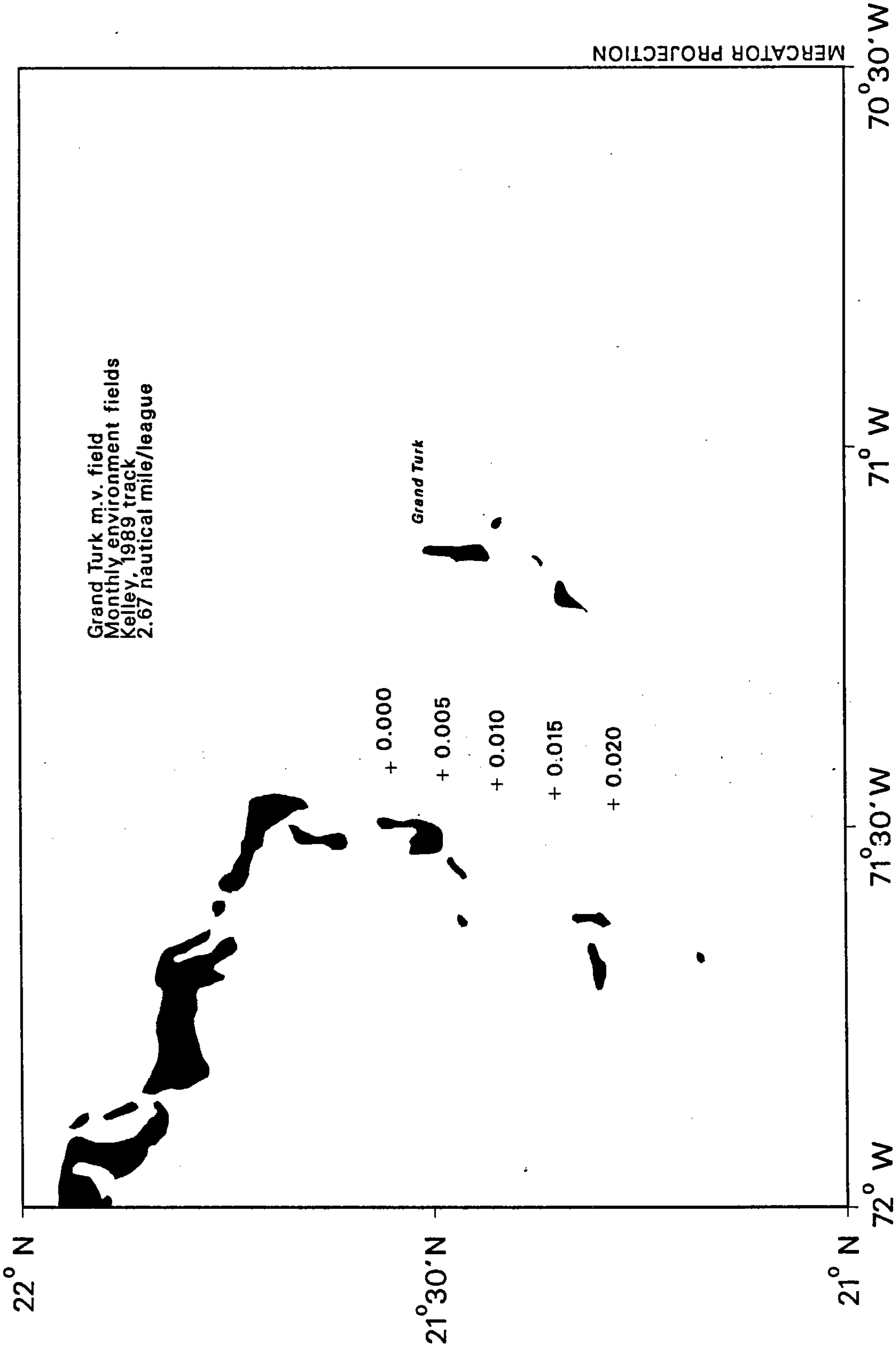

Figure 6: Effects of the leeway factor.

termination near Watling (San Salvador), the effect of leeway is almost the opposite. For the western Bahamas near San Salvador, leeway shifted the endpoint northwestward over a range of only 11 kilometers. The Turks and Caicos islands, being much further to the east, do not experience the more northerly current found in the western Bahamas nor the southerly turning of the winds characteristic of the October field further west. We find that the effects encountered during the beginning of the voyage in the eastern Atlantic are the predominant factors if the landfall is in the Turks and Caicos.

8 Effect of Errors in Heading and Speed

In order to accurately choose the correct landfall from the transatlantic voyage, accumulated navigational errors in its endpoint must be smaller than distances between the various landfalls. For example, to accurately choose between San Salvador and Grand Turk, Columbus' average course needs to be known to better than $\pm 3.5°$, the difference in course between these two landfalls when sailing from the Canaries, or his total distance needs to be known to better than ± 320 kilometers, the difference in distance between these two landfalls when sailing from the Canaries. Our tentative conclusion is that errors in the cruise endpoint are approximately this large, implying the simulated landfall cannot unequivocally be used to select the exact landing. Rather, the simulated landfall should be viewed as a location with a rather large uncertainty amounting to a few degrees in course error and a few hundred kilometers of distance error. We have discussed above the effect of magnetic field on the cruise endpoint. Here we investigate possible systematic and random errors in heading and speed. Random errors could have occurred, for example in the steering of the vessel as its heading varied slightly about the average course. With uniform fields of wind, current, and magnetic variation, random errors should tend to cancel and be smaller than systematic errors. Systematic errors would cause a cumulative effect over the whole voyage, such as may be produced by a persistent underestimate of the boat's speed. It is the systematic errors which have received the most investigation.

The course, as expressed in the Diario, was reported to the nearest compass point, a resolution of 11.25°. We think that Columbus' courses were steered with an accuracy much better than the implied resolution of 11.25°. Columbus attempted to steer due west from the Canaries and 80% of his reported headings are due west. We believe that he attempted to steer as accurately as possible and to record the courses as he steered them with no corrections.

To investigate the effect of random course errors we varied the heading by adding in a random offset. This was done by using a random number generator whose result was a uniform distribution of values ranging from −5.625° to +5.625°. The offset was applied to the reported course at each 30 minute leg of the track computation. The resulting termination points (cases 7a, b, c, d) are shown to vary about the nominal position within a radius of 6 kilometers (Figure 7). Thus, small discrepancies of actual heading from the reported course are not likely to have influenced the resulting track appreciably as long as the differences were random in nature.

In comparison, a systematic error in reported course such as would result from a misaligned or precalibrated compass could have a large effect. As the course was generally westward the effects of a compass offset are primarily a latitudinal deflection. Using the scenario for a Grand Turk landfall, a counterclockwise variation of the compass offset of 3.0° produced a deflection of the track terminus 265 kilometers to the southsoutheast (cases 5m, n). A 6° variation produced a linearly proportional effect (cases 5l, o). The assumed smoothness of the magnetic variation, or even the absence of a field (cases 5j, k) would produce a similar result for almost any terminus in the landfall debate. We do not know the accumulative error in Columbus' average course but estimate that it could be as large as ±2–3° or a quarter of a point. If this

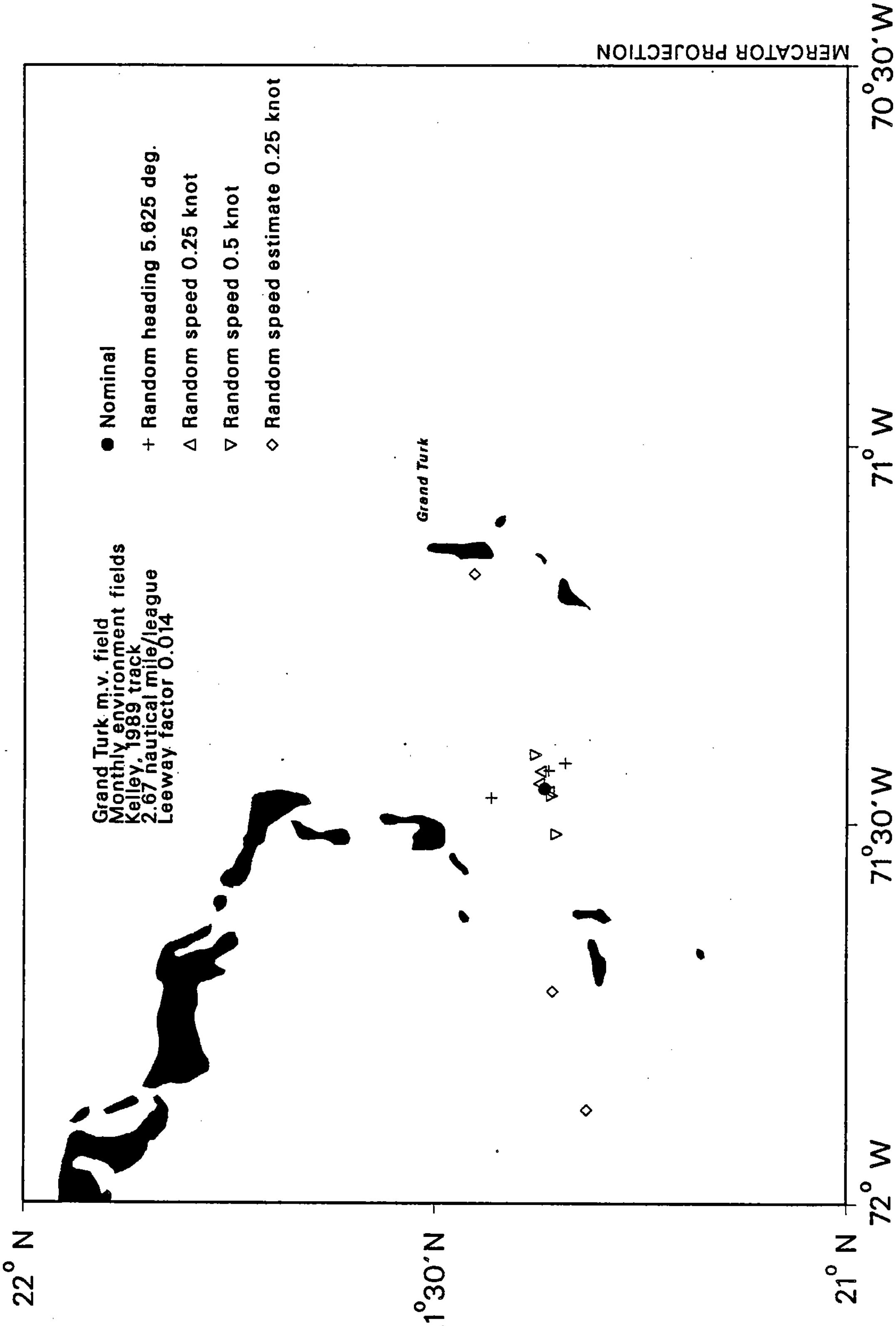

Figure 7: Effects of course and speed variations.

crude estimate is correct then the error in course is slightly smaller than the difference in the courses to San Salvador and Grand Turk when sailing from the Canaries. This says that the average course can be used to help locate Columbus' landfall, but that there is a rather large uncertainty with any simulated landfall. The best evidence of how well Columbus could reproduce his course comes from his second and fourth voyages when he sailed the same course westsouthwest from the Canaries to the Caribbean. His landfall on the second voyage was Dominica, on the fourth Martinique. Based on these two landfalls we estimate that his average courses agreed to within 1°–2° depending on whether we use the arc length between the centers of these islands or the arc length between the point half way between Dominica and Marie Galante on the north and the point halfway between Martinique and St. Lucia on the south. This 1°–2° includes both random and systematic errors.

The ship speed, in the form of distance traveled, is also subject to errors in observation. Random errors are likely to be encountered by mis-estimates of speed as a result of changing environmental conditions. Michael Richey (1989), former director of the Royal Institute of Navigation in England, believes that a practiced navigator like Columbus should be able to estimate his speed to within 0.25 knot (0.46 kilometers/hour). Using this figure as a maximum deviation in a normal distribution we applied a random offset to the speed used in each half hour track computation (cases 7e, f, g). For a number of simulations the termination points fell within a three kilometer radius of the nominal position. Increasing the maximum allowable deflection to a half knot increased the radius of scatter to 6.5 kilometers (cases 7h, i, j). Thus, random errors in the actual speed would hardly produce enough variation to cause uncertainty among the various island groups which contend for landfall honors.

If the variation in speed is instead applied to each of Columbus' log entries, the effect is more pronounced. Using the quarter knot maximum error, the radius of variation increased to almost fifty kilometers (cases 7k, l, m) or about 1% of the entire track distance. While this is a significant factor in pinpointing a landfall, it is still considerably short of the 5–6% uncertainty in the conversion factor of the historical league (the difference between the 2.67 and 2.819 nautical mile conversions). If we assume that Columbus incorrectly estimated by 0.25 knots his 3.8 knot average speed (averaged over the whole voyage), this amounts to a speed error of around 7% or a distance error of 350 kilometers. This value is around the same size as the difference in distance between the San Salvador and Grand Turk landfalls as sailed from the Canaries and suggests that even if we knew the exact league length, the total distance sailed has a rather large uncertainty. Kelley (1983) notes that the various estimates by Columbus and his pilots of the fleet's distance from the Canaries on September 19, 1492, agreed within 6% (the standard deviation of estimates around the mean). The distances were:

Nina's pilot	440 leagues
Pinta's pilot	420 leagues
Santa Maria's pilot	400 leagues
Columbus	436 leagues

On October 1 Columbus compared his estimates of 584 leagues with that of the *Santa Maria*'s pilot, 578 leagues, an agreement of 1%. Even if these do not provide an estimate of distance accuracy, they do suggest the relative consistency of distance estimates which range from 1%–6%.

If these crude estimates of error in course and speed are approximately correct then slightly more weight should be given to the landfall implied by a course deflection from a particular field of magnetic variation (assumed correct) compared to that implied by a particular league length (also assumed correct). A refinement in establishing the size of systematic errors is required to help us know how much confidence we can place on a simulated landfall.

9 Effects of Various Course Interpretations

While we chose to use the course as defined by Kelley (1989a), there exist other translations of the Diario and different interpretations of the course Columbus sailed (McElroy, 1941; Marden, 1986a; Goldsmith and Richardson, 1987). Fixing the other environmental conditions, we ran several scenarios using these other courses (cases 8a, b, c, d). As seen in Figure 8, the termination points for these cases generally lie northeast of Kelley's endpoint. The distance is about 85 kilometers (16 leagues) and is in the main accounted for by Kelley's assignment of a greater distance travelled during the night of 09 October.

10 Other Possible Sites for the First Landfall

There are many contenders for the site of the first landfall (see Parker, 1983) including Samana Cay (Judge, 1986), Watling Island (Obregon, 1986), Egg Island (Molander, 1983) and Grand Turk (Power, 1983; Power and Marvel, 1990). To explore the conditions needed to obtain a landfall at these various sites we repeated the exercise that was described earlier. Keeping all other factors constant, we varied the distance sailed and the magnetic variation at the landfall site until a reasonably close solution to each landfall was obtained (Table I, cases 14a, b, c, d). Each solution is certainly not unique; in fact there are an infinite number of solutions with just these two parameters. The listed magnetic variation is that used at the proposed landfall in the generation of the field. All fields here are based on two points, one at the Canaries (3°E), the second at the proposed destination.

The results show that the more northern landfalls require a larger league (because of the greater distance) and a smaller westerly magnetic variation. The southern landfalls require a smaller league and a larger westerly magnetic variation (to deflect

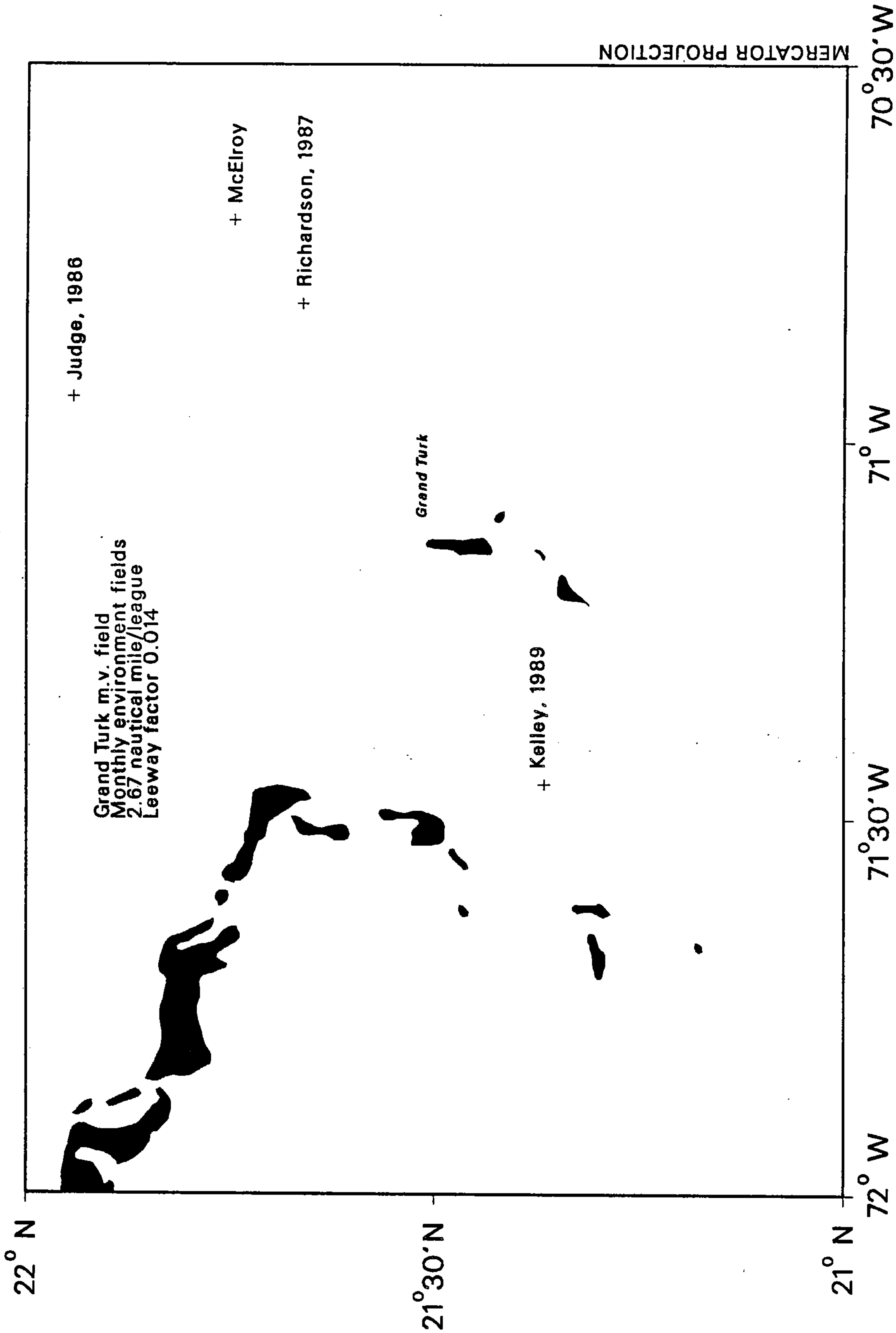

Figure 8: Effects of course interpretation.

the track southward). If no corrections for magnetic field are used, or if Columbus steered true courses, his cruise track would have ended at Great Abaco Island (just north of 26°N), and the estimated league length would have been 2.88 nautical miles.

11 The Voyage Back (to Santa Maria)

So far we have been concerned with sailing Columbus across the Atlantic and to his landfall. Given the course, as interpreted from the Diario, westerly magnetic field in the West Indies, vector average fields for the wind and currents, and a

Table I: Required league length and magnetic field for various hypothetical landfalls.

The listed values are those required for Columbus' track to end at each site (see text). The magnetic field used in these simulations was based on two points, one of 3°E at the Canaries and the other as listed at each hypothetical landfall.

Landfall	N. Mile /League	Magnetic Variation	Scenario Track Endpoint
Egg Island	2.867	3.9°W	3.2 km north
Watling Island	2.775	7.0°W	4.9 km south
Samana Cay	2.750	9.2°W	3.0 km south
Grand Turk Island	2.660	13.5°W	2.6 km south
Santa Maria[1]	2.740	–	24 km south
Dominica[2]	2.819	14.5°W	30 km east

1. Return voyage from Hispanola to Spain with intermediate stop at Santa Maria, Azores. The magnetic field used here is case 5a, the field for Columbus to arrive at Grand Turk.

2. Based on Columbus' second voyage which sailed from the Canaries to Dominica and a 850 league distance.

conversion factor of 2.67 nautical miles per league, it seems reasonable that Columbus would have landed somewhere near the Turks and Caicos Islands. Determination of the exact location is still largely dependent on the field of magnetic variation. Thus by holding all other factors constant, it still is possible to position a landfall almost anywhere desired within the range of the Caicos by varying the magnetic field.

In an effort to narrow the field of landfalls, two additional lines of investigation should be pursued. The first is the information to be gleaned from the subsequent inter-island journey. This trail seems to be unresolved by investigators and we do not pursue it here. The second approach lies in the use of data gained from the subsequent transatlantic voyages of Columbus. Any track generated from those voyages should be consistent with the factors determined in the first crossing. Thus, we will first look at the homeward leg of Columbus's voyage.

Columbus started his voyage back to Spain the morning of 16 January 1493 and arrived at the island of Santa Maria, in the Azores, on 15 February. To simulate this voyage we used a course furnished by Kelley (1989b), a league length of 2.67 nautical miles and monthly wind and current fields for January and February. First we tested the consistency of the magnetic field used in the outbound crossing (as in case 5a). Using that admittedly simple field we obtained a track termination (case 11a, Figure 9) at 36.449°N, 26.363°S around 121 kilometers (23 leagues) to the westsouthwest of Santa Maria. Although this represents only a good day's sail, it does not seem to be a very good result for the model. A second scenario (case 11b) was run using the course defined by Fuson (1987) which proved to be no better, ending up some 166 kilometers (32 leagues) to the south of Santa Maria. The model appears to produce a result somewhat short in latitude estimation. A test was made to determine the systematic error in speed (or league conversion factor) necessary to explain the shortfall. Increasing the league from 2.67 to 2.74 nautical miles reduces the shortfall to only 24 kilometers (case 11c). In fact, this corresponds to a position about 5 leagues

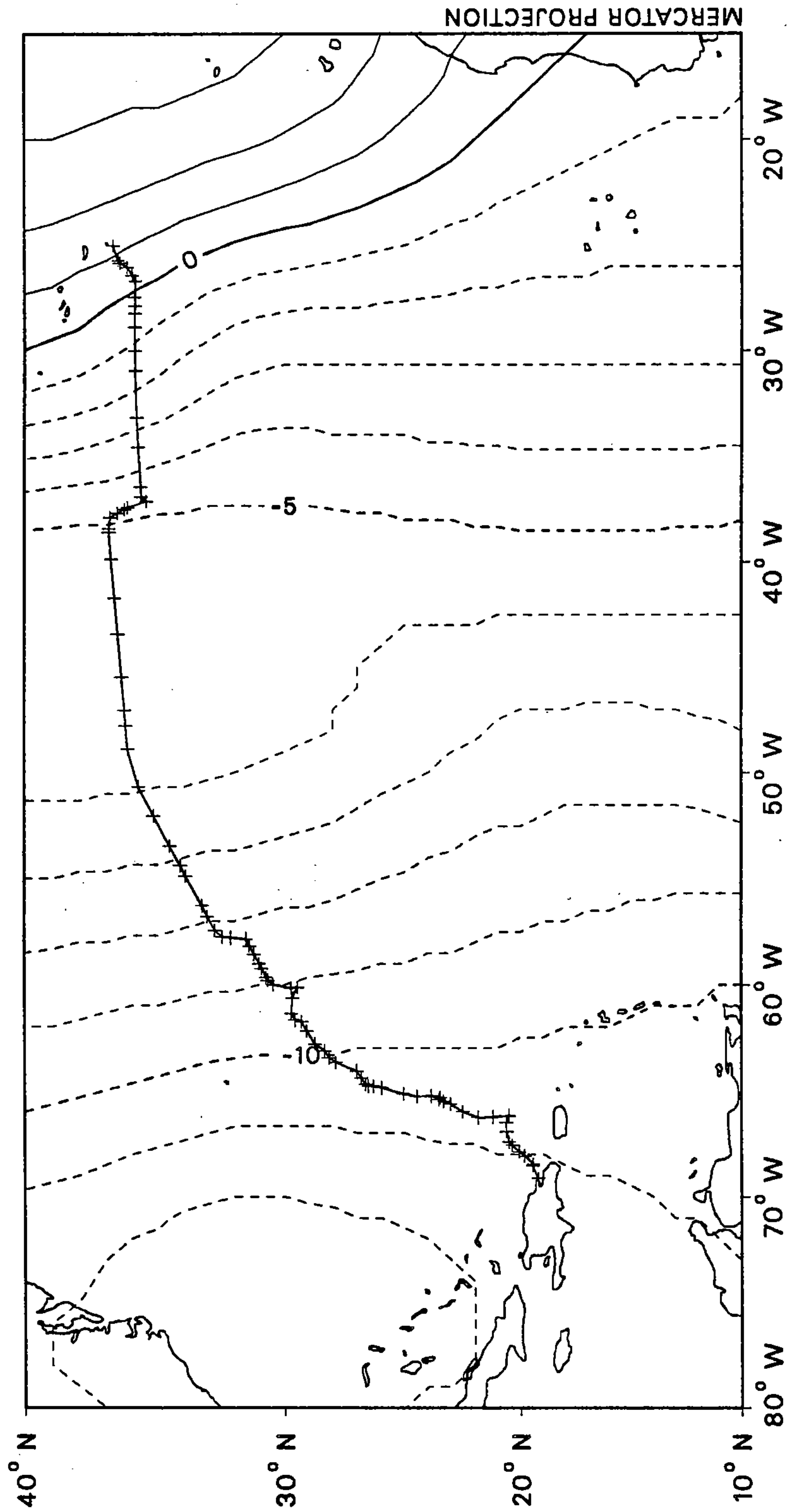

Figure 9: Return voyage to Santa Maria (Grand Turk field). Dashed line indicates westerly deflection.

south of Santa Maria and is close agreement with the position reported for 15 February. This scenario would be analogous to Columbus underestimating his speed by about 3% (assuming 2.67 nautical miles per league). A 2.819 nautical miles per league conversion factor would correspond to a 3% overestimate. In either case the effect is about the same as a systematic error of a quarter knot in speed as discussed above. Note that this distance is far less than the 450 km separating the Grand Turk and Watlings Island landfalls. In summary the length of a league for the Santa Maria landfall is closest to the Samana Cay value (Table I) but within the range of uncertainty of the Grand Turk value and the match in location suggests that the Grand Turk magnetic field is appropriate on the return voyage. That the simulated end point of the voyage back to Santa Maria is in close correspondence to the known arrival there suggests that the magnetic field hypothesized is not unreasonable.

A factor which may influence the definitive reconstruction of this track is the uncertainty of the progress made during the storm of 13 February. While there is no recourse but to accept Columbus's estimate of speed and heading in the 3 days around this date, the uncertainty discounts the possibility of an exact reconstruction. Further study might also focus on the refinement of the magnetic variation in the more northerly latitudes of this portion of the voyage.

12 The Second Voyage

What little direct evidence exists about Columbus's second voyage has been thoroughly described by Kelley (1988a). Columbus gave the sailing instructions to Dominica to the fleet captains prior to his third voyage, information apparently gleaned during his second voyage. To simulate the Canary–Dominica track, we used a course of 258.8° and a distance of 850 leagues over 21 days from 13 October to 3 November 1493. The field of magnetic variation was the same as used in the previous scenarios. The resulting termination point (case 12a) was found to lie well out to sea, some 320 kilometers (62 leagues) from Dominica (Figure 10). We looked for a league conversion factor which would produce the correct distance, all other factors remaining constant (case 12b). A league of 2.819 nautical miles was just about correct. The terminus was still about 170 kilometers (33 leagues) north of the island however. To determine the magnetic variation that would result in the fleet's arrival at Dominica, we followed the same general procedure as performed earlier; we began with the field generated for the Turks and Caicos landfall (GT) and changed the magnetic variation at Dominica until a suitable field was generated. A 2.819 nautical mile per league conversion factor and a deflection of 14.5°W at Dominica (case 12c) reduced the separation distance to about 30 kilometers (9 leagues) with the endpoint lying east of the island. Dominica is 1440 meters high and can be seen on a clear day from a distance of 130–150 kilometers at sea. As Columbus told his captains they would only be "near" the island, this scenario seems valid. It is possible that the vector average current fields, based as they are on long time scale climatological data, are less appropriate as the voyages become shorter in both duration and distance. Without knowing more about the details of the voyage it is difficult to estimate the representativeness of the conditions.

In summary, the magnetic field required for the Dominica landfall appears to be consistent with that required for the Turks and Caicos landfall (Table I). The length of the league, however, matches those for Watlings and Egg Island landfalls. Assuming the 2.67 nautical miles/league length to be correct, Columbus' error in distance to Dominica was around 6%.

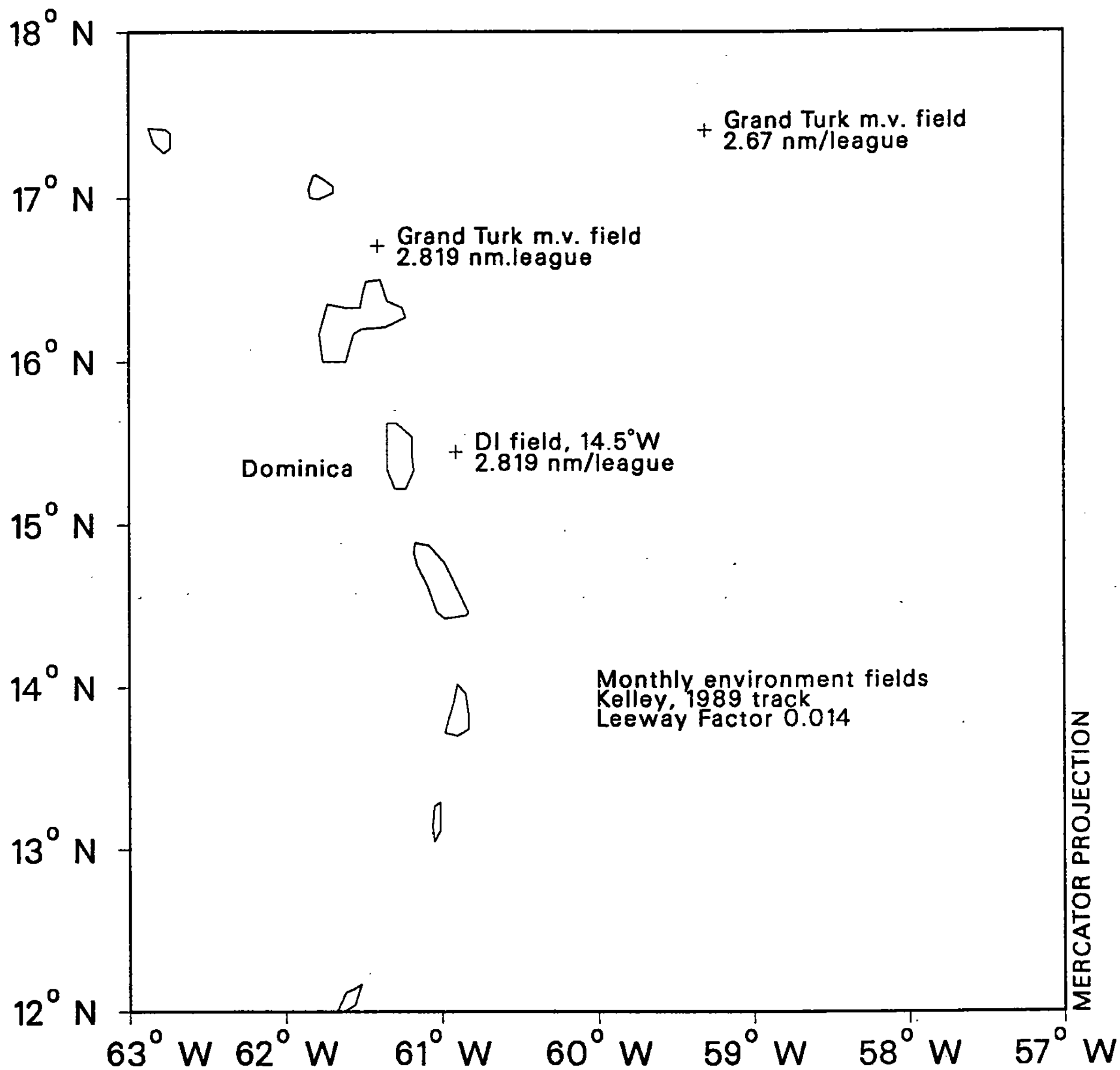

Figure 10: Second voyage terminus at Dominica.

13 The Third Voyage

We have done little with the third voyage as yet although we recently obtained some relevant information from Kelley (1989b). He offered some data and thoughts from his preliminary analysis of Columbus's trip across the Venezuelan Basin, from Margarita to Madam Beata, Hispanola. We used the course reconstructed by Kelley and the magnetic variation determined in the Dominica scenario as that seemed to be the closest point applicable. For this case we resumed use of the 2.67 nautical mile league. Interestingly, this produced a terminus at 17.721°N, 71.419°W, not far off the mark (case 13b). This is about 35 kilometers (6 leagues) north of the expected arrival point, but given the uncertainty of the distance for the first two days, it is not unreasonable. The important features are that the currents and the magnetic variation seem to give a consistent result. The currents are very strong and consistent in this region and the vector averages probably do not appreciably differ from the pilot charts. The approximately 15°W magnetic variation for the region also appears favorably with other lines of investigation.

14 Summary

Our simulations have explored the effects of the length of a league and the historical magnetic field on the endpoint of Columbus' first voyage. We found that the Grand Turk landfall is consistent with a Geometric league of 2.67 nautical miles and a westerly magnetic variation of around one point (11.25°) in the West Indies. The return voyage to Santa Maria in the Azores and Columbus' second voyage to Dominica are also consistent with this hypothetical magnetic variation. The inferred league length on the return voyage (2.74 nautical miles) is larger than the Geometric league inferred for Grand Turk, more in agreement with a landfall near Watling Island. The inferred length for the trip to Dominica (2.819 nautical miles) is also larger than that for Grand Turk, more consistent with those for Watlings and Egg Island. However, the standard error of the six possible league lengths inferred from these three voyages (Table I) is 0.071 nautical miles or 2.6% of their average (2.769 nautical miles), well within the estimated error of this quantity as discussed below.

The biggest problems in reconstructing the track and endpoint of the first voyage are uncertainties in the league length and in the 1492 field of magnetic variation. Documenting the league length to within a few hundredths of a mile and the variation within a few degrees is required to help pin down the cruise endpoint. The largest uncertainties in the endpoint given a specific magnetic field and a specific league length are the poorly known systematic navigational errors. We estimate that these could be as large as ±2–3° in the average course steered by Columbus and a few hundred kilometers in the total distance sailed. The distance error is based on an estimated average speed error of 0.25 knots which is around 7% of the average cruise speed. The size of the error in total distance is about as large as the difference in distance along tracks from the Canaries to San Salvador and to Grand Turk and the error in average course is slightly smaller than the angular difference in these tracks. Thus, even though our simulations using a Geometric league and westerly magnetic variation point to a landfall in Grand Turk, the uncertainty of this landfall is quite large. If the systematic errors in navigation are smaller than we have estimated, then of course, our simulated endpoint would have a smaller uncertainty and we could place more confidence in the landfall established from the transatlantic cruise. Thus, our conclusion is that given a Geometric league and a westerly variation of around one point the probability is higher for a southern landfall (near Grand Turk) compared to a mid or northern Bahama landfall. The exact probability is very difficult to estimate.

Compared to the uncertain league length, the poorly known magnetic field and systematic errors described above, the other factors are considerably smaller but not insignificant. The various wind and current fields caused variations around 30 kilometers in the endpoint. This suggests that inaccuracies in the historical winds and currents would have a relatively small effect in altering the track termination. While it is possible that unusual conditions existed during September and October 1492 there is no evidence for this in Columbus' log entries. The various translations and interpretations of the log show differences in the endpoint of around 45 kilometers, primarily alongtrack. Random errors in Columbus' speed and course tended to cancel and their accumulated effect was smaller than this.

Acknowledgements

We are grateful to James Kelley for sharing with us his data and analysis. While we have affixed his name as a label to some of the analysis, the results do not necessarily reflect his views. We would also like to thank Josiah Marvel for several suggestions regarding lines of investigation to pursue and Robert Power for his helpful discussions concerning the landfall question. Finally, we appreciate the timely and professional assistance provided by Mary Ann Lucas in preparing this paper.

This work was funded by a grant from the Nova Albion Foundation and the Government of the Turks and Caicos Islands. We extend our thanks for the support to continue this investigation, the forum to present these results, and the chance to visit Grand Turk and San Salvador.

References

Dunn, O., and J. E. Kelley, Jr., 1989. The Diario of Christopher Columbus's first voyage to America 1492–1493. Univ. of Oklahoma Press, 491 pp.

Fuson, R. H., 1987. The log of Christopher Columbus. International Marine Publishing Co., Camden, Maine, 252 pp.

Goldsmith, R. A., and P. L. Richardson, 1987. Reconstructing Columbus's First Transatlantic Track and Landfall Using Climatological Winds and Currents, *Technical Report 87-46*, Woods Hole Oceanographic Institution.

Judge, J., 1986. Where Columbus Found the New World. *National Geographic*, **170**, 567–599.

Kelley, J. E., Jr., 1983. In the wake of Columbus on a Portolan Chart. *Terrae Incognitae*, **15**, 77–111.

Kelley, J. E., Jr., 1987. The navigation of Columbus on his first voyage to America. *Proceedings, First San Salvador Conference. Columbus and His World.* Compiled by Donald T. Gerace, Fort Lauderdale, Florida: CCFL Bahamian Field Station, pages 121–140.

Kelley, J. E., Jr., 1988a. 19 December 1988, Preliminary estimates of magnetic variation along Columbus's route on his second voyage to the new world (MAGVAR1). Unpublished manuscript.

Kelley, J. E., Jr., 1988b. The map of the Bahamas implied by Chaves' *Derrotero*. What is its relevance to the first landfall question? Unpublished manuscript.

Kelley, J. E., Jr., 1989a. 14 September 1989 memo to Robert Power.

Kelley, J. E., Jr., 1989b. 17 October 1989 memo, personal correspondence.

Marden, L., 1986a. Navigation data from the Atlantic passage: entries in the Columbus log. In: *A Columbus Casebook*, A Supplement to "Where Columbus Found the New World," pages 48–50.

Marden, L., 1986b. The First Landfall of Columbus. *National Geographic*, **170**, 572–577.

Marvel, J., 1988. Memo 21 September 1988.

McElroy, J. W., 1941. The ocean navigation of Columbus on his first voyage. *The American Neptune I*, **209**, 240.

Molander, A. B., 1983. A new approach to the Columbus landfall. *Terrae Incognitae*, **15**, 113–149.

Obregon, M., 1986. Columbus' first landfall, San Salvador. In: *Columbus and His World, Proceedings of the First San Salvador Conference, October 30–November 3, 1986*. College Center of the Finger Lakes, Bahamian Field Station, Fort Lauderdale, Florida, 185–195.

Parker, J., 1983. The Columbus landfall problem: A historical perspective. *Terrae Incognitae*, **15**, 1–28.

Power, R. H., 1983. The discovery of Columbus's Island passage to Cuba, October 12–27, 1492. *Terrae Incognitae*, **15**, 151–172.

Power, R. H., and J. Marvel, 1990. Evidence that Grand Turk Island was Christopher Columbus's first landfall in the New World. Unpublished manuscript.

Richardson, P. L., and R. A. Goldsmith, 1987. The Columbus landfall: voyage track corrected for winds and currents. *Oceanus*, **30**(3), 3–10.

Richey, M., 1989. Lecture: The conquest of the oceans; navigation in the discovery and colonization of the Americas. At the John Carter Brown Library, Providence, R.I., September 26, 1989.

Schott C. A., 1881. An inquiry into the variation of the compass off the Bahama Islands, at the time of the landfall of Columbus in 1492. Report of the Superintendent of the U. S. Coast and Geodetic Survey for the year 1880. Appendix No. 19, 412–417, Washington.

Van Bemmelan, W., 1899. Die Abweichung der Manetnadel. In: *Supplement to Observations of the Royal Magnetical and Meteorological Observatory at Batavia 21*, Batavia.

Appendix 1 — Summary of Track Parameters and Termination Positions for Cases Presented

		Termination			League	Mag	-- Corrections --			
Fig.	Case	Lat	Lon	Track	conv	var	curr	wind	leeway	Notes
1	0a	23.766	-74.359	PLR1a	2.819	vB	aut.	aut.	0.014	
	0b	23.745	-74.343	PLR1a	2.819	vB	aut.	aut.	0.014	
1	1a	23.575	-75.084	JEK1a	2.819	vB	aut.	aut.	0.014	
1	1b	23.674	-72.074	JEK1a	2.67	vB	aut.	aut.	0.014	
	2a	22.408	-71.293	JEK1a	2.67	JM2	aut.	aut.	0.014	
	2b	21.321	-70.927	JEK1a	2.67	JM2	aut.	aut.	0.014	1
2	3a	23.079	-71.754	JEK1a	2.67	MC10W	aut.	aut.	0.014	
2	3b	21.106	-71.062	JEK1a	2.67	MC15W	aut.	aut.	0.014	
	3c	19.160	-70.289	JEK1a	2.67	MC20W	aut.	aut.	0.014	
2	3d	21.704	-71.282	JEK1a	2.67	GT1	aut.	aut.	0.014	
2,5	3e	21.610	-71.377	JEK1a	2.67	GT	aut.	aut.	0.014	
3,5	5a	21.367	-71.454	JEK1a	2.67	GT	mon.	mon.	0.014	
5	5b	21.923	-71.380	JEK1a	2.67	GT	Sep.	Sep.	0.014	
5	5c	21.591	-71.435	JEK1a	2.67	GT	Oct.	Oct.	0.014	
	5d	25.853	-72.734	JEK1a	2.67		mon.	mon.	0.014	
	5e	26.047	-75.725	JEK1a	2.819		mon.	mon.	0.014	
	5f	26.232	-76.936	JEK1a	2.88		mon.	mon.	0.014	
	5g	21.967	-69.959	JEK1a	2.67	GT			0.014	
	5h	21.757	-69.918	JEK1a	2.67	GT		mon.	0.014	
5	5i	21.551	-71.422	JEK1a	2.67	GT	mon.		0.014	
	5j	28.251	-73.195	JEK1a	2.67		mon.	mon.	0.014	5
	5k	23.507	-71.578	JEK1a	2.67		mon.	mon.	0.014	6
	5l	25.985	-72.783	JEK1a	2.67	GT	mon.	mon.	0.014	7
	5m	23.674	-72.140	JEK1a	2.67	GT	mon.	mon.	0.014	5
	5n	19.044	-70.833	JEK1a	2.67	GT	mon.	mon.	0.014	6
	5o	16.769	-70.245	JEK1a	2.67	GT	mon.	mon.	0.014	8
6	6a	21.551	-71.422	JEK1a	2.67	GT	mon.	mon.	0.000	
6	6b	21.488	-71.432	JEK1a	2.67	GT	mon.	mon.	0.005	
6	6c	21.422	-71.444	JEK1a	2.67	GT	mon.	mon.	0.010	
6	6d	21.352	-71.456	JEK1a	2.67	GT	mon.	mon.	0.015	
6	6e	21.281	-71.470	JEK1a	2.67	GT	mon.	mon.	0.020	
7	7a	21.367	-71.454	JEK1a	2.67	GT	mon.	mon.	0.014	
7	7b	21.362	-71.430	JEK1a	2.67	GT	mon.	mon.	0.014	2
7	7c	21.342	-71.420	JEK1a	2.67	GT	mon.	mon.	0.014	2
7	7d	21.432	-71.466	JEK1a	2.67	GT	mon.	mon.	0.014	2
7	7e	21.372	-71.431	JEK1a	2.67	GT	mon.	mon.	0.014	9
7	7f	21.374	-71.447	JEK1a	2.67	GT	mon.	mon.	0.014	9
7	7g	21.362	-71.458	JEK1a	2.67	GT	mon.	mon.	0.014	9
7	7h	21.378	-71.409	JEK1a	2.67	GT	mon.	mon.	0.014	10
7	7i	21.352	-71.514	JEK1a	2.67	GT	mon.	mon.	0.014	10
7	7j	21.358	-71.463	JEK1a	2.67	GT	mon.	mon.	0.014	10
7	7k	21.356	-71.721	JEK1a	2.67	GT	mon.	mon.	0.014	11
7	7l	21.315	-71.877	JEK1a	2.67	GT	mon.	mon.	0.014	11
7	7m	21.453	-71.171	JEK1a	2.67	GT	mon.	mon.	0.014	11
8	8a	21.367	-71.454	JEK1a	2.67	GT	mon.	mon.	0.014	
8	8b	21.663	-70.817	PLR1a	2.67	GT	mon.	mon.	0.014	
8	8c	21.943	-70.941	MJ1a	2.67	GT	mon.	mon.	0.014	
8	8d	21.748	-70.707	McE1a	2.67	GT	mon.	mon.	0.014	
	9a	21.322	-71.689	JEK1a	2.67	GT	mon.	mon.	0.014	3
	9b	21.353	-71.486	JEK1a	2.67	GT	mon.	mon.	0.014	4
9	11a	36.449	-26.363	JEK1c	2.67	GT	mon.	mon.	0.014	
9	11b	35.475	-25.258	RHF1c	2.67	GT	mon.	mon.	0.014	
9	11c	36.741	-25.031	JEK1c	2.74	GT	mon.	mon.	0.014	
10	12a	17.406	-59.313	JEK2a	2.67	GT	mon.	mon.	0.014	
10	12b	16.705	-61.409	JEK2a	2.819	GT	mon.	mon.	0.014	
10	12c	15.447	-60.910	JEK2a	2.819	DI	mon.	mon.	0.014	
	13b	17.721	-71.419	JEK3b	2.67	DI	mon.	mon.	0.014	
	14a	25.635	-76.575	JEK1a	2.867	EI	mon.	mon.	0.014	
	14b	24.019	-74.342	JEK1a	2.775	WI	mon.	mon.	0.014	
	14c	23.065	-73.546	JEK1a	2.75	SC	mon.	mon.	0.014	
	14d	21.429	-71.139	JEK1a	2.66	GT2	mon.	mon.	0.014	

All tracks used course headings rounded to tenths of a degree.
All tracks used distance travelled rounded to tenths of a league.
All cases used rhumbline positioning method unless noted.
All cases used a 24 hour day, ie. no day length adjustments unless noted.
All cases used the 30 minute computation interval unless noted.

Track codes:

PLR1a	First voyage outbound, Richardson, based on Marden.
JEK1a	First voyage outbound, J. E. Kelley memo of 14 Sep., 1989.
MJ1a	First voyage outbound, Marden/Judge, November, 1986.
McE1a	First voyage outbound, McElroy.
JEK1c	First voyage homeward, J. E. Kelley memo of 17 Oct., 1989.
RHF1c	First voyage homeward, R. H. Fuson, 1987.
JEK2a	Second voyage outbound, from Kelley.
JEK3b	Third voyage, Venezuela Basin crossing, from Kelley.

Magnetic variation code:

vB	As proposed by vanBemmelen for 1500 ad.
JM2	As proposed by J. Marvel, memo of Oct, 1988.
MC10W	Generated with a -10.0 variation at the mid Caicos group.
MC15W	Generated with a -15.0 variation at the mid Caicos group.
MC20W	Generated with a -20.0 variation at the mid Caicos group.
GT1	Generated with a -13.3 variation at Grand Turk Island.
GT	Generated with course observations to landfall at Grand Turk.
SM	GT field modified with trial observations.
DI	Magnetic variation field modified for landfall at Dominica.
WI	Magnetic variation field modified for landfall at Watling Island.
SC	Magnetic variation field modified for landfall at Samana Cay.
GT2	Magnetic variation field modified for landfall at Grand Turk.

Current and wind field codes:

aut	Autumnal, vector average of September and October fields.
mon	Average fields for date corrected month.
Sep	September field used for entire track.
Oct	October field used for entire track.

Note 1: Used an applied compass correction of -1.8 degrees.
Note 2: Used random variation on 0.5 hour heading (normalized 5.625 degrees).
Note 3: Day adjustment used, lengthened for track to the west.
Note 4: Great circle positioning used but on the 30 minute interval.
Note 5: Used an applied compass correction of +3.0 dregrees.
Note 6: Used an applied compass correction of -3.0 dregrees.
Note 7: Used an applied compass correction of +6.0 dregrees.
Note 8: Used an applied compass correction of -6.0 dregrees.
Note 9: Used random variation on 0.5 hour speed (normalized 0.25 knot).
Note 10: Used random variation on 0.5 hour speed (normalized 0.50 knot).
Note 11: Used random variation on leg speed (normalized 0.25 knot).

Appendix 2 — Prevailing Current Versus Vector Average Current

Marden (1986b) corrected Columbus' transatlantic track by using prevailing currents given on pilot charts of the North Atlantic. We used vector average currents for this purpose because they are more representative of how a ship is carried by ocean currents. To understand why, consider a buoy drifting in an ocean current. As the buoy drifts, it will usually meander and occasionally loop in ocean eddies. The mean displacement of the buoy or how far it was carried by the current is equal to the vector mean velocity of the buoy over a time interval multiplied by the interval. The mean velocity must include the loops and meanders in order to be representative of the real buoy displacement. However, the way prevailing currents are calculated excludes those current vectors that are not in the same general direction as the vector average direction. Thus prevailing currents tend to overestimate current speeds and are not representative of how far a buoy or a ship would be carried by currents.

To understand the difference between prevailing currents and vector average currents we need to see how the two quantities are calculated. The basic data are measurements of ocean currents by the set and drift of ships. The U.S. Naval Oceanographic Office has accumulated these data over the last 150 years. A prevailing current shown on the pilot charts is determined by first calculating the vector average velocity in a particular region using all the individual current measurements in that region. Then the scalar average speed is calculated using only the individual velocity values lying within a 45° sector containing the vector average direction. A plotted arrow on the chart represents the vector average direction and the plotted speed in knots is the average speed of those values lying within the 45° sector.

The problem with the average speed calculated by this method is that measured current velocity values going in the other 7 sectors or 315° are ignored. Along Columbus' route the prevailing current determined by ship drift is around 0.46 knots, much bigger than the vector mean velocity which is around 0.12 knots. Individual velocity measurements are distributed in all 8 sectors. By using only those values in the one sector containing the vector average direction, the resulting scalar average speed is inflated several times larger than the vector average velocity which uses all velocity values within a region no matter what their direction.

The size of a velocity measured by ship drift is determined by both real ocean fluctuations and errors in the ship drift technique. Random errors, which can be large in these measurements, tend to cancel in vector averages of velocity but do not cancel in the 45° sector averages of speeds. Thus part of the difference between a vector average velocity and prevailing current speed is due to measurement error.

In summary, we think that prevailing currents have two strikes against them. First, they are not representative of vector average currents even when errors are ignored. Second, when errors are present, they cause the apparent prevailing current speed to be artificially inflated.

In practice we grouped individual ship drift measurements in 2° latitude by 5° longitude boxes and calculated the vector average velocity for each box. The size of the box was a trade off between being large enough to contain a sufficiently large number of values so that a statistically significant vector average could be calculated over a uniform region, and being small enough to be able to resolve and map geographical variations in the average current field. We then interpolated these 2° × 5° box averages into a 1° × 1° grid with which we corrected the track for current drift.

Appendix 3 — Summary of Evidence for Westerly Historical Magnetic Variation in the West Indies

Virtually all early maps of the West Indies show the islands plotted several degrees north of their true latitude with the westernmost islands offset the farthest north. For example, on the Juan de la Cosa map of 1500, Dominica is around 4° too far north, and the north coast of Hispanola is around 7° too far north. The simplest explanation and the one we believe to be correct is that westerly magnetic variation set early navigators imperceptibly southward as they sailed across the Atlantic. Early navigators like Columbus primarily used dead reckoning; they sailed with a magnetic compass for course and estimated their speed and distance through the water (M. Richey, personal communication). When these explorers made a landfall in the West Indies they thought they were farther north than they really were and plotted the newly discovered islands too far north. Some early charts attempted to aid navigators by showing two different latitude scales, one in the east for Europe and Africa and a second in the west for the West Indies and America, to show their correct latitudes. We believe that Columbus was set southward on his voyages by westerly magnetic variation which explains his first voyage report that Hispanola was located at 26°N versus its true latitude of 20°N (the north coast). Although Columbus reported rough estimates of magnetic variation three times on his first voyage, we think his estimates were too crude for him to correct his course and that he steered the exact courses he logged. He made no mention of latitude sights and therefore was not following a constant latitude with such observations.

Columbus' reported 26°N latitude for Hispanola matches closely our estimated latitude of his landfall in our simulation that assumed he steered courses true, as presumably he thought he was doing. Columbus says that the landfall islands were on the latitude of Hierro, around 27.7°N, so he must have thought he sailed almost due westward. One can argue that the 1.7° difference in latitude between his 26°N and the

27.7°N of Hierro is just about equal to the 1.5° difference between the north coast of Hispanola and Grand Turk. If Columbus really first landed farther north than Grand Turk, say at Egg Island at 25.6°N, why did he say Hispanola was 26°N. He would have sailed from 25.6°N south to 20°N to reach Hispanola, and he would have known that 26°N was incorrect for its latitude. The same argument can be made for Watling Island and Samana Cay.

Direct evidence for westerly magnetic variation is given in Chaves' Espejo de Navigantes (see Kelley, 1988b; Appendix 3). Chaves describes navigation from Spain to the Indies circa 1533 and says to navigate from Hierro one should sail 800 leagues on course W by SW (258 3/4°) to arrive at LaDeseada, Guadalupe or Dominica (three closely spaced islands). He says that magnetic variation will deflect the track south by 60 leagues (around 180 miles). This allows one to compute the average value of compass variation on the Hierro–Deseada route as 4.2°W (Molander, personal communication). Assuming that variation was 3°E in the Canaries and linearly increased westerly toward Deseada, we estimate Deseada's variation to be 11.4°W, or nearly one point. The important points here are (1) the average westerly magnetic variation was clearly documented and (2) the method of following a magnetic course to the Indies and the effect of variation on that course was clearly described in writing shortly after Columbus' voyages. We are convinced that Columbus would have had a rather similar southward deflection by magnetic variation on his first voyage. Although the magnetic variation could have changed somewhat between 1492 and 1533, the rather short time span implies that the magnetic fields were probably quite similar at the two times. Columbus' second voyage followed the same course as later recommended by Chaves and arrived at Dominica, a little south of Deseada. Thus our reconstruction of the magnetic field calculated at a slightly larger magnetic variation of 14.5°W for Dominica. Our simulation also included corrections for winds and currents which influenced the exact value. The inferred magnetic variation for Dominica and Deseada at the two times is just about what is required in the vicinity of Grand Turk for Columbus' voyage to end there. In summary we think there is ample evidence that westerly magnetic variation occurred in the vicinity of the West Indies and that it caused Columbus' course to be set imperceptibly southward. Documenting the exact field of magnetic variation in the Atlantic and West Indies will permit us to infer how much Columbus was set southward and help reveal his first landfall. The evidence to date implies that Grand Turk is a reasonable choice for the first landfall based on the transatlantic voyage.

Appendix 4 — Alonso de Chavez, *Espejo de Navegantes*, (c1530) published for the first time by the Museo Naval, Madrid, 1983.

Chaves's formula for reaching the Leeward Islands is given in Lib. IV, Cap. i, *De la navegacion de Espaóa a las Indias.*

Navigation from Spain to the Indies, and principally that departing from the Port of Sanlúcar de Barrameda or from the Port of Cadiz, which all the pilots and navigators are accustomed to and hold as the best and most certain route, is, by departing from the places abovementioned, to guide their route the way of the southwest and, navigating by this rhumb 230 leagues, they will reach the Island of Tenerife or Gomera which are Islands of the Canaries, at which, having taken refreshment and necessary provision, they take their route by the same southwest rhumb to the Island of Hierro, which is the most western and southern of all the islands of the Canaries, and being so far advanced as the said Island of Hierro by the south side and near it, they ought to make this consideration. If the sailing charts which they should bring be made for courses (as they are said) [ie marked with windroses and not for latitude and longitude], in such case departing from the place abovementioned, they ought to run the way to the west quarter southwest, and going the whole way correcting their route with the latitude, which is necessary by cause of the currents and weather, and having run by the abovesaid quarter 800 leagues, they will reach la Deseada, or Guadalupe [sic pro Marigalante], or Guadalupe or La Dominica in the Islands of the Cannibals, because they are so much distant from Hierro. And if the charts be made for latitudes as they are called, that one sole graduation is understood, in such a case, because while crossing the whole gulf [of the Ocean] the needles make very great variation and declination, such a remedy must be provided for, that being at the Island of Hierro at the time of the departure, they take 60 leagues with the dividers, which 60 leagues are measured directly south from the said Island of Hierro and at the end of them you have a point which you have to fix which is the said Island of Hierro [for charting purposes], and from this point you have to go setting down your point and your courses and distances. And you will leave from the Island of Hierro and will order to run on the west quarter southwest, and as soon as the ship departs from the island, depart you with your point from the other point, which likewise you have to guide by the quarter of the southwest which goes parallel and distant by the 60 leagues to that which departs from the said island. In such a manner that, departing from the said Island, and with the ship and with the point after the other point, and both by the said quarter, having gone 800 leagues, the point and the ship will join themselves on the Island Deseada or on the others adjacent to it.

A third manner and best or most brief and certain: On the sailing chart which you have made for latitudes, draw a line with a rule that passes from the Island of Hierro and running and running [sic] to the west quarter southwest for the northwesting and declination of the needles. In such a manner that, the said line being drawn, you will depart from the said Island of Hierro to the west quarter southwest and will go setting down the point by that line which you drew, because in truth, departing from the said Island by the said cuarta, the ship makes its route by the line abovesaid by reason of the declination that the needles make. In such a manner, as always they should navigate from the said Island of Hierro for the said Indies by some one of the three manners abovesaid, one must order to run by the west quarter southwest, having firstly made the abovesaid diligences, and it is to note that the manner most certain and brief is this which I here write, never before now heard of nor exercised, and the said line which thus should be drawn unmarked, signaling only a ray with a lead or other thing for that it may obscure with the others, and be clear in order to put the point, which points, after the navigation is made, may be taken out for that it be clear for another time.

The authors thank Mr. Josiah Marvel for providing this translation.

DOCUMENT LIBRARY

March 11, 1991

Distribution List for Technical Report Exchange

Attn: Stella Sanchez-Wade
Documents Section
Scripps Institution of Oceanography
Library, Mail Code C-075C
La Jolla, CA 92093

Hancock Library of Biology & Oceanography
Alan Hancock Laboratory
University of Southern California
University Park
Los Angeles, CA 90089-0371

Gifts & Exchanges
Library
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, NS, B2Y 4A2, CANADA

Office of the International Ice Patrol
c/o Coast Guard R & D Center
Avery Point
Groton, CT 06340

NOAA/EDIS Miami Library Center
4301 Rickenbacker Causeway
Miami, FL 33149

Library
Skidaway Institute of Oceanography
P.O. Box 13687
Savannah, GA 31416

Institute of Geophysics
University of Hawaii
Library Room 252
2525 Correa Road
Honolulu, HI 96822

Marine Resources Information Center
Building E38-320
MIT
Cambridge, MA 02139

Library
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

Library
Serials Department
Oregon State University
Corvallis, OR 97331

Pell Marine Science Library
University of Rhode Island
Narragansett Bay Campus
Narragansett, RI 02882

Working Collection
Texas A&M University
Dept. of Oceanography
College Station, TX 77843

Library
Virginia Institute of Marine Science
Gloucester Point, VA 23062

Fisheries-Oceanography Library
151 Oceanography Teaching Bldg.
University of Washington
Seattle, WA 98195

Library
R.S.M.A.S.
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149

Maury Oceanographic Library
Naval Oceanographic Office
Stennis Space Center
NSTL, MS 39522-5001

Marine Sciences Collection
Mayaguez Campus Library
University of Puerto Rico
Mayaguez, Puerto Rico 00708

Library
Institute of Oceanographic Sciences
Deacon Laboratory
Wormley, Godalming
Surrey GU8 5UB
UNITED KINGDOM

The Librarian
CSIRO Marine Laboratories
G.P.O. Box 1538
Hobart, Tasmania
AUSTRALIA 7001

Library
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside L43 7 RA
UNITED KINGDOM

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-92-14	2.	3. Recipient's Accession No.

4. Title and Subtitle **Numerical Simulations of Columbus' Atlantic Crossings**	5. Report Date February 1992
	6.
7. Author(s) Roger A. Goldsmith and Philip L. Richardson	8. Performing Organization Rept. No. WHOI-92-14
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543	10. Project/Task/Work Unit No.
	11. Contract(C) or Grant(G) No. (C) (G)
12. Sponsoring Organization Name and Address Nova Albion Foundation and the Government of the Turks and Caicos Islands	13. Type of Report & Period Covered Technical Report
	14.

15. Supplementary Notes

This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-92-14.

16. Abstract (Limit: 200 words)

The transatlantic route of Columbus was simulated incorporating historical winds, currents and hypothetical magnetic variation in order to estimate where the first landfall occurred. Earlier simulations using an 1899 map by Van Bemmelen and assuming zero magnetic variation in the Bahamas to produce a landfall near San Salvador (Watlings Island). New theories postulating a Geometric league of 2.67 nautical miles and a westerly magnetic variation of approximately one point (11.25) for the western terminus result in a landfall near the Turks and Caicos Islands. A westerly variation of this magnitude in the Bahamas has been inferred from early charts – the islands are shown several degrees too far north, which would have occurred if early navigators had been set imperceptibly southward by westerly variation – by studies of directions within the islands, and by studies of early navigation books. The simulation of subsequent voyages by Columbus lend further weight to a westerly variation of about one point in the region of Bahamas. Our work shows that a Grand Turk landfall cannot be ruled out based on the transatlantic portion of the voyage as has been suggested in the past. A more accurate simulation of the voyage and first landfall still requires a more accurate representation of the field of magnetic variation.

17. Document Analysis a. Descriptors

Columbus voyage
historical currents
magnetic compass navigation

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Approved for public release; distribution unlimited.	UNCLASSIFIED	45
	20. Security Class (This Page)	22. Price