ASTRONOMICAL AND SAILING TABLES FROM THE SECOND HALF OF THE 15TH CENTURY TO THE MIDDLE OF THE 16TH CENTURY

Edoardo Proverbio, Osservatorio Astronomico, Cagliari.

1. From dead reckoning to latitude navigation.

1.1 Merit for having bestowed great impetus on oceanic sailing along the coasts of Africa in search of a possible route to the Indies must go to the "Infante" Henry (1394-1460), son of King John I of Portugal (1357-1433)**(1)**. This sailing the *high seas*, or *per peleggio* (from the Greek pelàghei = high seas)**(2)**, immediately led to the necessity of establishing the ship's position in latitude while sailing towards the equator. It is known that from the oldest times, navigators and pilots used the Sun's position as a reference point by day and that of the Pole Star, or Polaris, by night, to orient themselves while sailing along the routes of the Mediterranean. They observed the Sun and stars before they had the use of the compass to steer the ship in the right direction and keep to their course. There are many literary references to the use of the stars in steering ships that go back to Roman times **(3)**. Among these, the verses that the Florentine Monte Andrea, an imitator of Guittone d'Arezzo, wrote to his lady between 1259 and 1280 appear significant:

Si como i marinar guida la stella
che per lei ciascun prende suo viaggio.

Also the "stella maris", to which the Spaniard Raimundo Lullo (1232?-1315) refers in his De quaestionibus geometriae, must be considered as being among the instruments necessary for steering ships along the chosen course and in calculating distance at sea **(4)**.

Only in sailing the high seas in the orient and with the beginnings of oceanic navigation did the Pole Star cease to be used in reckoning the direction of the ship and begin to be used in establishing its position in latitude.

Observations of the height of the pole with natural instruments for estimating the position of the ship in latitude came into use starting at least from the 13th century **(5)**, but it is from the time that the Spanish and Portuguese began sailing along the coasts of Africa (first half of the 15th century), that it became necessary to determine latitude more precisely by measuring the length of the day **(6)** with the use of the first graduated instruments for measuring altitudes.

The first latitude measurements performed with marine quadrants and astrolabes at northern latitudes must necessarily have relied on the traditional method used in observing the Pole Star. The oldest record of such observations is the one reported by Diego Gomes in the diary of his voyage to Guinea, the Azores and the Cape Verde Islands **(7)**.

Columbus himself, who sailed in northern latitudes on his first two voyages, reaching latitudes 8°- 9° on some occasions during his third and fourth voyages, used the Pole Star for his latitude observations in all cases, if we are to rely on available evidence. It is to be stressed that up to about 1490-95, no importance was given in these observations to changes in the altitude of the Pole Star, which around 1492 was 3°27' from the North Pole. The method used in observing the Pole Star for latitude measurement was, in any case, well known to medieval astronomers, and in the "Libros del Saber de Astronomia", promoted by Alfonso X of Castile (1223-1284), drawn up by a group of Arab, Hebrew and Christian scientists and presumably printed in 1276-77, very precise rules were laid down for observation of the Pole Star and the circumpolar stars in the two culminations so as to find the astronomical latitude **(8)**.

The quite surprising fact that pilots in the second half of the 15th century were unaware of this movement may perhaps be explained by the fact that since the first latitude observations at sea were imprecise and made with inaccurate instruments, it was not considered necessary to make corrections that at most would have led to errors of 3° in latitude. A second, and probably more realistic, explanation of the lack of a correction for the height of the Pole Star at sea may be that no almanacs were available for the distance from the North Pole of the Pole Star itself, since this datum was of no use to professional astronomers. This made such a correction quite problematic and placed it outside the reach of pilots. If to this we add the initial objective difficulties encountered by the Portuguese in creating valid structures for the establishment of rules for use by navigators based on a solid grounding in astronomy, we can perhaps find a plausible explanation of why latitude observations made at sea with the Pole Star up to about 1490 were made with such uncertainty.

Only on his second (1493) and third (1498) voyages did Columbus appear to refer explicitly to latitude observations of the Pole Star at the maximum degressions **(9)** and lower culmination **(10)**.

The fact remains, however, that the first empirical rules that took into account the distance of the Pole Star from the North Pole were established perhaps some time around 1480-81 and circulated in manuscript form, of which one edition, probably that of 1509, printed in Lisbon **(11)**, is extant. But in the decade from 1470 to 1480, when oceanic navigation took sailors to the Equator **(12)** and even beyond, observations of the Pole Star were no longer possible. At that point, navigators began relying on observations of the Sun at midday to determine latitude.

Given the Sun's declination $\underline{\delta}$, measurement of the Sun's elevation at noon made it possible to calculate the ship's latitude.

1.2 As long as navigators kept to the lower northern latitudes, observers were presented with three distinct cases, as represented in **Figure 1 (13)**. The Sun could be south of the Equator (S_1), north of the Equator but south of the Zenith (S_2), north of the Equator and Zenith (S_3). In all three cases, latitude had to be calculated by means of rules, which could be expressed as relations:

$$\varphi = \delta_1 + (90^\circ - h_1) \quad , \qquad (1)$$
$$\varphi = \delta_2 + (90^\circ - h_2) \quad , \qquad (2)$$
$$\varphi = \delta_3 - (90^\circ - h_3) \quad , \qquad (3)$$

Given the pilot's or observer's difficulty in deciding case by case which of the three relations was to be used, it became necessary to give specific instructions concerning this choice as a function of the value of the Sun's declination at the moment or day of the observation and the direction of the shadow of a vertical gnomon at the instant of the Sun's culmination (meridian passage).

In the following Table are represented the different conditions of declination and shadow of the gnomon from which the navigator could choose the rule best suited for calculating latitude:

Sun's Declination	Direction of gnomon shadow	Rule used
$\delta_1 \leq 0$	towards North	(1)
$\delta_2 \geq 0$	towards North	(2)
$\delta_3 > 0$	towards South	(3)

The need to determine latitude in equatorial and austral zones with a certain degree of accuracy by observing the Sun at midday thus made sailing techniques far more complicated. The application of these techniques, in fact, called not only for possession by the pilot of sufficiently sophisticated astronomical and mathematical knowledge to perform the calculations, but also required his being in possession of accurate tables of the Sun's declination.

At this point, questions arise concerning the history of the development of astronomical sailing techniques, which up to now have received insufficient attention.

By what means and in what structures were pilots and others to whom the determination of astronomical coordinates at sea was entrusted prepared to make use of these techniques?

What was the relationship between professional astronomers and the officials and state organizations in Portugal and Spain that were giving such impetus to the great oceanic voyages in the 15th and 16th centuries, a crucial period in the history of sailing?

What specific astronomical knowledge was used or referred to by experts and astronomers engaged in the establishment of general rules for latitude, and later astronomical navigation, and in the compilation of the necessary nautical tables?

We shall now attempt to supply answers, although certainly not final, to at least the last of these questions.

2. Astronomical and nautical tables in the period from the 15th to the 16th centuries.

2.1 The oldest references to astronomical latitude observations of the Sun at sea are apparently those made by Columbus on his voyage to Guinea at the time of his sojourn in Portugal (1479-84)**(14)**, the observations made in Guinea by Master Josephus (1485)**(15)**, and those made by Bartolomeo Diaz at the time of his rounding the Cape of Good Hope (1487-88)**(16)**. Later, in the first half of the 16th century, other latitude measurements at sea were made with sailor's quadrants and astrolabes. Some longitude measurements, of which sure documentation is extant **(17)**, were also made. Unfortunately, in the documents now in our possession concerning the latter voyages and the latitude measurements performed, there are very few mentions of the nautical tables used in these latitude or longitude determinations: that is to say, the tables of the length of the day, the Sun's declination, planetary conjunctions and eclipses, which pilots must necessarily have consulted in calculating these coordinates.

In the course of the 15th century, among professional astronomers and compilers of calendars and astronomical almanacs, the tavole del primo mobile or tabulae directionum of the Bolognese Giovanni Bianchini (first half of the 15th century) **(18)**, of Johann Müller, known as Regiomontanus(1436-1475), who taught astronomy in Vienna following the death of his master Georg Peuerbach (1461)**(19)** and of the Jew Abraham Zacuto (15th century)**(20)** became well known.

Astronomical tables concerning the primo mobile and their rules were often independent of the more general tables, including those of the motion of the planets, and were generally divided into: tables of the declination of the signs of the Zodiac and the Sun, trigonometric tables of sines and chords, tables of time equations (difference between real and mean time), tables of right and oblique ascensions of the signs of the Zodiac and other tables more of interest to mathematicians than to astronomers (tabula proportionum, etc.)**(21)**. Most of these tables depended on the value used for the obliquity of the ecliptic, which thus constituted an element of differentiation between one table and another. In fact, measurement of the obliquity of the ecliptic was one of the main goals of Arab astronomers and observational astronomy in general which, in Italy, and especially in Germany, was then in a phase of development.

Of the medieval tables, the most renowned and used up to the Renaissance were the Toledan Tables (1080)**(22)** and the Alfonsine Tables (1252)**(23)**. Consequently, many later authors adopted the values for the obliquity of the ecliptic and the precession constant on which these tables were based when compiling their almanacs. Giovanni Bianchini e Abraham Zacuto referred to the Alfonsine Tables in drawing up their tabulae directionum, using the obliquity value of 23°33', on which the "Libros del saber de astronomia" **(24)** were based, in calculating the Sun's declination and other tables. Regiomontanus instead, in his Tabulae directionum, the first edition of which goes back to 1490, adopted the value of 23°30' for obliquity, which was deduced from his own observations of the Sun's meridian height **(25)**. It is to be presumed that he used the same value in compiling the Calendarium for the years from 1475 to 1531, printed some time around 1475, and in the Ephemerides for the years 1482 to 1506, which appeared in 1481.

It must also be kept in mind that even quite some time after the appearance of the Alfonsine Tables, a certain number of writers of treatises and compilers of almanacs still referred to the Toledan Tables, in which obliquity was evaluated at 23°33'30 **(26)**. For example, in his Tractatus Sphaerae, the Genoan Andalò di Negro (1260?-1340?), at several points referred to the latter value for obliquity **(27)**, although he then unexpectedly calculated (or copied) the longitudo longioris diei, that is, the day's length at the summer solstice, using the obliquity adopted by Ptolemy (23°51'20) **(28)**.

In the second half of the 15th century, therefore, three major astronomical sources were accessible for reference in deriving the values of the Sun's declination, the day's length and other astronomical phenomena (planetary conjuntions and oppositions, eclipses), which were becoming more and more important in sailing the seas. It is to be noted in **Table 1**, which gives the theoretical obliquity values calculated in the different epochs, that while the Toledan and Alfonsine tables appear to be sufficiently accurate for the epochs in which these tables were drawn up, they are clearly erroneous if compared to the theoretical value and the new obliquity value deduced by Regiomontanus towards the end of the 15th century.

Table 1

Epoch	**Theor. Obliquity**	**Adopted Obliquity**	**Tables**
1080	23°33'32"	23°33'30"	Toledan
1252	23°32'12"	23°33'00"	Alfonsine
1490	23°30'20"	23°30'00"	Regiomontanus

Taking into account the precision of measurements of the Sun's altitude at noon made with graduated instruments during the 15th and 16th centuries, these differences did not introduce important errors in the tables of declination and observed latitudes. They are, however, of great importance in attempting a reconstruction of the different ways in which the knowledge and astronomical skills developed in the different cultural areas were learnt by the pilots and elaborated on by them, and in the new maritime areas in which, first in Portugal and then in Spain, a true revolution was taking place in techniques and rules for the piloting of ships and in the organization of the great sailing enterprises.

2.2 As has been said, Prince Henry of Portugal (1394-1460) was the inspirer of the first oceanic ventures, but his was also the merit of creating a sailing academy, apparently for the main purpose of producing naval charts, as the presence of the Jew James of Majorca**(29)** (who was expressly sent there by Prince Henry, would appear to indicate), at Sagres, near Cape Saint Vincent some time around 1420. In fact, it appears to be certain that under the name of Master James we find the renowned instrument-maker and cartographer Jafuda Cresques, son of the equally famous cartographer Abraham Cresques, author of Charles V's Catalan atlas **(30)**. Lacking adequate documentation, it is impossible to glean more precise information on activities at the academy in Sagres, at least up to about 1480 when, on the initiative of John II (1455-1495), Henry's nephew **(31)**, and, like his uncle most senisitve to the need for reorganizing sailing methods, a "junta" of experts was appointed to set up new rules for use by pilots in latitude sailing. Barros, who gives us this precious information, specifies that the "junta" was composed of Master Josephus (José Vizinho), Master Rodrigo, the King's physician, and Martin de Behem (Martinus de Boemia) **(32)**, the famous German cartographer, who sojourned in Portugal between 1480 and 1491, and then from 1493 onwards **(33)**.

We do not know exactly when this "junta" was formally set up (apparently some time between 1480 and 1485 **(34)**), nor do we know if other experts in astronomy and the drawing up of charts were formally members of the committee. The Spaniard Diego Ortiz **(35)**, a close friend of his fellow-countryman Juan da Salaya, who in 1481 was the first to translate into Spanish Zacuto's, Almanach which was presumably available in the form of manuscript copies, was certainly among the experts to whom John II turned. Zacuto, following his arrival in Portugal (1492), certainly did join the group of astronomers and cartographers working in the service of John II, and, after the latter's death (1495), of King Emanuel, to set up new rules for sailing by the height of the Pole Star and the Sun at midday **(36)**.

It is within the framework of this group of technicians that a first series of rules (regimentos) for pilots must have been drawn up in Portugal, together with tables giving the distance of the Pole Star from the North Pole and the Sun's meridian declination. These rules and the previously mentioned tables that accompanied them, which presumably were available as manuscript copies starting from 1480-1483 **(37)**, were perhaps printed for the first time around 1495 **(38)**, and became what is held to be the oldest Portuguese sailing manual, the Regimento do astrolabio e do Quadrante, of which the edition printed in Lisbon in about 1509, conserved in Munich and known as the Munich Table **(39)**, is extant. The manual contains a series of rules and tables that announce the passage from pre-astronomical sailing to latitude sailing. The essential part of the Regimento contains, in fact, a kind of almanac of the distance of the Pole Star (estella do Norte) from the pole, based on rules fixing the distance as a function of the position in the sky of the two stars at the extremities (β and γUMi) of the constellation of Ursa Minor. The position in the sky of these two stars, known as the guards (guardas), is established with reference to the directions of the main winds making up the classic wind rose. In **Table 2** are given the values in degrees of the distances of the Pole Star from the North Pole indicated in the Regimento, concerning the eight principal directions of the wind rose, presumably estimated on the basis of experience accumulated by pilots during their voyages on which, starting from about the middle of the 15th century, latitude observations were performed by observing the (variable) height of the Pole with graduated instruments.

It is interesting to note that the polar distance values established in the 1509 Regimento were in practice adopted, with no changes, up to the second half of

Table 2

Correction to apply to Pole Star observations for latitude determinations (in degrees).

Principal winds & Pos. of "Guards"		Cortes 1551	Medina (1545) 1554	"Regimento" 1509	True polar distances(1500)
0	N	+ 3	+ 3	+ 3	+ 2½
22.5	NNE		+ 3½		+ 3¼
45	NE	+ 3½	+ 3½	+ 3½	+ 3½
67.5	ENE		+ 3		+ 3¼
90	E	+ 1½	+ 1½	+ 1½	+ 2½
112.5	ESE		+ ½		+ 1 1/3
135	SE	- ½	- ½	- ½	0
155.5	SSE		- 2		- 1 1/3
180	S	- 3	- 3	- 3	- 2½
202.5	SSW		- 3		- 3¼
225	SW	- 3½	- 3½	- 3½	- 3½
247.5	WSW		- 3		- 3¼
270	W	- 1½	- 1½	- 1½	- 2½
292.5	WNW		- 1		- 1 1/3
315	NW	+ ½	+ ½	+ ½	0
337.5	NNW		+ 2		+ 1 1/3

the 16th century in later treatises on sailing. In these ephemerides, the position of the Pole Star is assumed to be, counting the angles clockwise, at about 135° from the position of the Guards; therefore, since the latter are in direction SW (225°), the Pole Star should be found in the higher culmination (360°), that is, in direction North, to which was attributed a distance from the Pole of 3°½, a fairly accurate value if one observes the data in Table 3.

Table 3

Values of the polar distance of αUMi in the15th and 16th centuries.

Epoch	**Polar distance**
1450	3°42'
1500	3°25'
1550	2°52'

Comparing the polar distance values contained in the "Regimento" with those of about the year 1500 (see Table 2), it can be seen that the maximum excursion, that is, the latitude error of 1°, is associated with the symmetrical positions E e W of the Guards.

The Munich Tables contain, day by day from 1st March, the position of the Sun in the signs of the Zodiac and its meridian declination **(40)**.

This is the most important and significant datum emerging from the "Tables", by means of which it became possible to determine latitude at sea by observing the Sun. It is to be observed, as has been said, that the use of these tables required not only the knowledge of the day, which gave the sign of the declination, but also the derivation from the shadow of a stylus if the meridian altitude of the Sun observed, or its complement, was to be added to or subtracted from the declination in order to obtain the latitude. In practice, the simple rules given in the manual were a substitute for relations (1), (2) and (3) illustrated previously, and guaranteed the correct use of the new method for determining the ship's position with respect to the Equator.

The calculation and its variation also indicated to the pilot the exact distance travelled along the course. For this purpose, the manual also contained a table of latitudes between the Equator and Cape Finisterre (lat. 43° N) and a table, in the form of a rule, giving the exact distance in leagues corresponding to a variation of 1° of latitude in one of the eight directions of the wind rose **(41)**.

This new technique for measuring distance as a function of latitude variation constituted a significant step forward, not lastly because of its simplicity, compared to the method used up to then, which was quite laborious and based on the use of rules that had to be learnt by rote **(42)**.

It is to this group of experts brought together at the Court of King Emanuel of Portugal that we owe the drawing up and publication, between 1517 and 1528, of a second important manual for navigators, the Regimento da declinaçam do Sol, printed in Lisbon and known as Évora's Table or Manual **(43)**.

It appears certain that the Munich Tables and É vora's Table, and in particular the tables of the Sun's declination contained in them, which were produced in different epochs by groups of experts at the Portuguese Court, were respectively and directly derived from the Toledan and Alfonsine Tables, the former, as we have seen, based on the value of 23°30'30", and the latter on that of 23°30' for the obliquity of the ecliptic **(44)**.

The hypothesis of a common origin of the first Portuguese nautical tables from the Alfonsine Tables by way of those derived from Zacuto's thus appears to be unfounded **(45)**.

Nor is it unreasonable to hold that the Munich Tables, which had already been produced in manuscript form around 1480-83, that is, before the setting up of the first and second "juntas" by John II, were the fruit of the work of other Portuguese and Spanish experts and scholars who, in computing the Sun's declination, had turned to the Arzachiel Tables which, as has already been pointed out, were frequently used even after the diffusion of the Alfonsine Tables, as, for example, the tables calculated by the Jew Jacob ben Mahir ibnTibbon (whose Latin name was Prophatius) for the year 1301 with reference to the meridian of Montpellier, and those, already mentioned, contained in the Tractatus Sphaerae by Andalò di Negro (see Table 1). With this hypothesis, the work of the junta in 1485, compared to the Munich Tables, can be viewed as that of a committee with the task of editing material already in part compiled and further developed by contributions originating from the experience of skilled pilots, some of whom were already using, on an individual basis, tables of the Sun's declination. It is in fact known that Columbus himself, quite some time before embarking on his voyage to the Indies, and presumably already at the time of his sojourn in

Portugal (1479-1484), had drawn up a table of the Sun's declination and one of the length of the day, the latter clearly taken from the Toledan Tables **(46)**.

It may be held that Jose Vizinho's contribution, and that of Zacuto's after 1492, was oriented in the direction of further compilations of tables for navigators. In the Landas de India, the Portuguese Gaspar Correa supplied some precise details concerning the drawing up of new tables of the Sun's declination for the cycle from 1497 to 1500 for Vasco da Gama's expedition, and the designing of new kinds of sailors' astrolabes by Zacuto on the request of John II **(47)**. The existence of astronomical tables prepared by Zacuto for Alboquerques' fleet (1503) is further confirmed by Gaspar Correa **(48)**. Whether or not Évora derived his tables from these must remain, for the moment, an open question. **Table 2** represents an attempt to reconstruct the ascendency of Évora's tables from Zacuto's nautical tables, for the existence of which there appears to be only indirect evidence.

2.3 In the same year as the recognition of the Kingdom of Castile and Aragon (1479), John II, who was in his eighties, died. King Ferdinand II began the decisive struggle to eliminate the last Arab strongholds in Spain. The fall of Granada in 1492, the same year as Columbus's voyage to the Indies, may be said to mark Spain's commitment to great sailing enterprises.

In 1503, the Casa de Contratacion, which later came to represent a crucial element in the development of practical and theoretical research into sailing techniques, was founded in Seville **(49)**.

The beginnings of the 16th century thus witnessed, with some ups and downs, the consolidation of Spain's supremacy in the organization of oceanic voyages which, on reversing a tendency that had begun in the last decades of the 15th century, saw the arrival in Seville, and at the Spanish Court, of expert pilots, (such as Magellan) and skilled cartographers and astronomers (such as Faleiro), from Portugal. From the death of Amerigo Vespucci (1454-1512) to 1516, the office of Piloto Mayor, which is to say in practice the technical and scientific director of the Casa de Contratacion, was entrusted to the Portuguese navigator Juan Diaz de Solís, who was followed by the Venetian Sebastian Cabot, who remained in office up to 1548 **(50)**.

We do not know if among the duties of the experts working at the Casa de Contratacion there was that of creating tables of the Sun's declination or other astronomical almanacs, which by that time were in general use in latitude sailing. The activity of the Casa was then in fact prevalently concentrated on the production of charts and the realization of graduated instruments for measuring heights **(51)**.

The fact remains that the first Spanish nautical manual containing tables of the Sun's declination and rules for the observation of the height of the Pole is the Suma de Geographia, written by the Sevillian Martin Fernandez de Enciso, and goes back to 1519 **(52)**. From the Sun's declination at the solstices (23°33'), given with the precision of the primes of arc, it is not easy to establish the astronomical sources from which Enciso took inspiration in compiling his declination tables. Waters attributes, but we do not know on what grounds, the sources of the declination tables contained in the Suma to the tables drawn up by Zacuto for the solar cycle from 1497 to 1500 **(53)**, for the existence of which we have only indirect evidence.

It appears that these declination tables were then published in the second edition of the Suma, which appeared in 1530, referring to the four-year solar cycle from 1529 to 1532 and which were also included in the Tratado del Esphera y del arte del marear, written by the Portuguese Francisco Faleiro while in the service of Spain, and printed in Seville in 1535 **(54)**. It cannot be excluded that the latter tables had been created by Ruy Faleiro, Francisco's brother, who was an expert in astronomy and cartography and a close collaborator of Magellan's, with whom he left Portugal some time around 1518 and settled in Spain after his failure to convince King Emanuel to sponsor a voyage towards the Moluccas following a westerly course.

If the derivation of the first Spanish nautical tables from those by Zacuto, which in my opinion is not sufficiently documented, can be justified *a posteriori* on the basis of the existence of ancient traditions in Spain in the field of astronomy, of which the University of Salamanca, in which Zacuto had worked, was one of the centres, it is rather surprising that in one of the most widely diffused treatises, not only in Spain, but also among Dutch, Italian, French and in part English pilots in the middle of the 16th century, the table of the Sun's declination appears to derive from the Toledan Tables, presumably by way of the Munich Tables drawn up in Portugal. Pedro de Medina, in his Regimento de navigacion dedicated to Prince Don Felipe, son of Charles V, the first edition of which, printed in Villadolid in 1545 **(55)**, gives the value of 23°33' for the maximum declination of the Sun. But this value, approximated to the primes complicates the problem of a derivation from the Alfonsine Tables. In any case, if we accept the idea that Medina's tables of the Sun's declination contained in the first edition published in 1545 derive from Évora's or from Enciso's Suma, how are we to explain the fact that in the 1554 French edition of Medina's work, which appeared under the title L'Art de Naviguer **(56)**, side-by-side with the four-year tables of the Sun, which are the same as those in the first edition of 1545, we find a table added with no explanation in which the Sun's declination is given day by day to the fourth minutes, and in which the maximum declination assumes the value of 23°33'33"? At this point we must conclude that the editor of the French edition inserted this table while referring to a different astronomical source of Toledan derivation compared to the one used by Pedro de Medina or that, on the contrary, on the basis of documents that have not come down to us, the editor felt it would be a good way to render explicit the direct source of Medina's tables. It must be added that in this French edition there are two more tables, which did not appear in the first edition, that give the day's length as a function of latitude, the first of which manifestly calculated with the obliquity value of 23°30° given in Regiomontanus' tables, while the second appears to follow, up to about latitude 50°, Columbus' table of the length of the day, on the average based on the value 23°33'30 of the obliquity taken from the Toledan Tables. Unexpectedly, beyond the 60° latitudine, the length of the day is clearly derived from the Ptolemaic tables and adopted by other medieval writers of treatises, among whom, as has been said, we find Andalò di Negro **(57)**. The variety of ascendencies of the latter tables contained in the French edition of Medina's work denotes great uncertainty on the part of the editor in compiling the tables, and shows the difficulty encountered in deriving the astronomical sources of the nautical tables in use in the first half of the 16th century. A diagram of the possible ascendencies of the nautical tables drawn up in Portugal and later in Spain in the first half of the 16th century is given in **Tables 1 and 2** and mentioned previously.

2.4 The table of the day's length contained in the 1554 edition of the Arte del Navegar, which was derived from the obliquity value of 23°30' given by Regiomontanus, may perhaps be placed in some sort of relationship with the last great sailing manual of the middle of the 16th century drawn up by Martin Cortès and published in Seville in 1551. In his Breve compendio de la sphera y de la arte de navegare **(58)**, Cortèz in fact made use of the obliquity value of 23°30' in the tables of the Sun's declination.

It therefore seems that starting from the middle of the 16th century, Regiomontanus' tables, in ways that still remain to be ascertained, began to be used in Spain, and later in other maritime centres, in calculating the nautical ephemerides. It is to be pointed out that a table of the Sun's declination based on Regiomontanus' tables appears in the atlas attributed to the Genoese cartographer Francesco Ghisolfi, which was drawn up some time in the second half of the 16th century **(59)**.

On the other hand, Rodrigo Rasurto, who taught astronomy at the renowned University of Salamanca following Zacuto's departure, is known to have published, as early as 1494, a supplement to Regiomontanus's Ephemerides **(60)**, which demonstrates that the tables of the famous German astronomer began to become known in Spain in those places in which astronomical knowledge was developing and that they were applied at the Casa de Contratacion in Seville and by the experts in sailing techniques as far back as the end of the 15th century, as can be seen from the reconstruction proposed in **Table 3**.

The preliminary results summarized in Tables 1, 2 e 3 indicate the possible itineraries by which certain basic astronomical concepts became assimilated and were used in the form of rules, instructions and pilot's manuals in the centres in which the new astronomical sailing techniques were being developed in Portugal and later inSpain.

The research, performed on the basis of an analysis of the main astronomical and nautical tables created up to about the middle of the 16th century, still leaves unsolved some not secondary problems. We believe that more convincing results may be obtained through an analysis of different documents and material, in part published, but for the most part available only in archives and unfortunately of difficult access, concerning the activities of the university institutes (Salamanca) and the first sailing schools of the epoch.

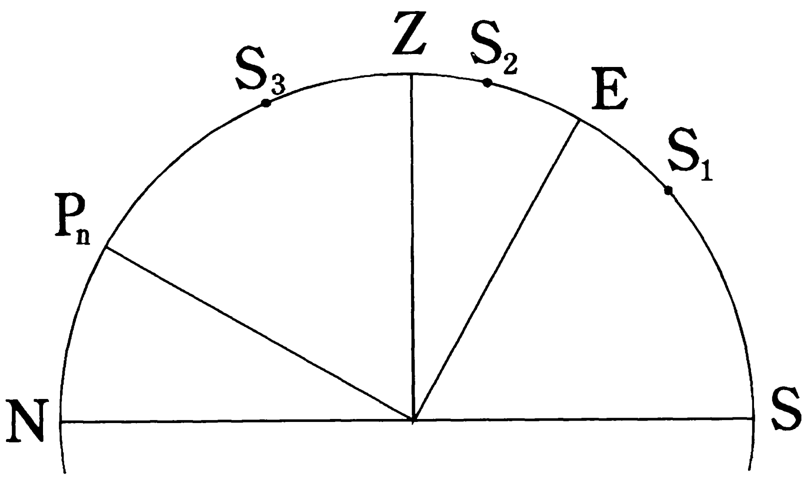

Fig.1. Three possible cases of observation of the Sun's altitude S_i (i = 1,2,3) at the meridian for latitude determination at sea (N= North, S=South, Z=Zenith, P_n = North Pole, E=Equator).

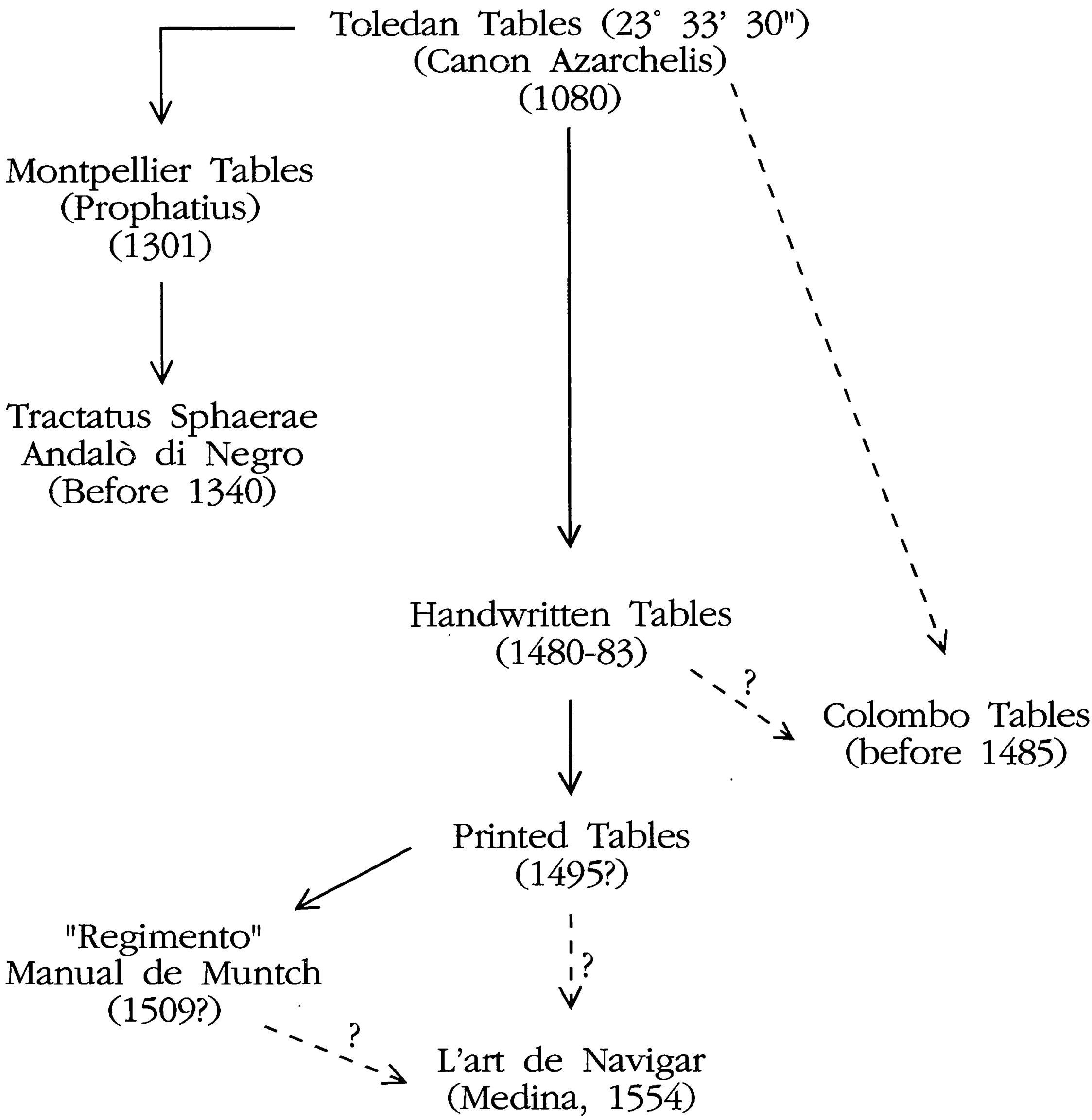

Table 1. Diagram of the probable development of nautical charts derived from Arzachel's astronomical Tables (Toledan Tables), up to the middle of the 16th century.

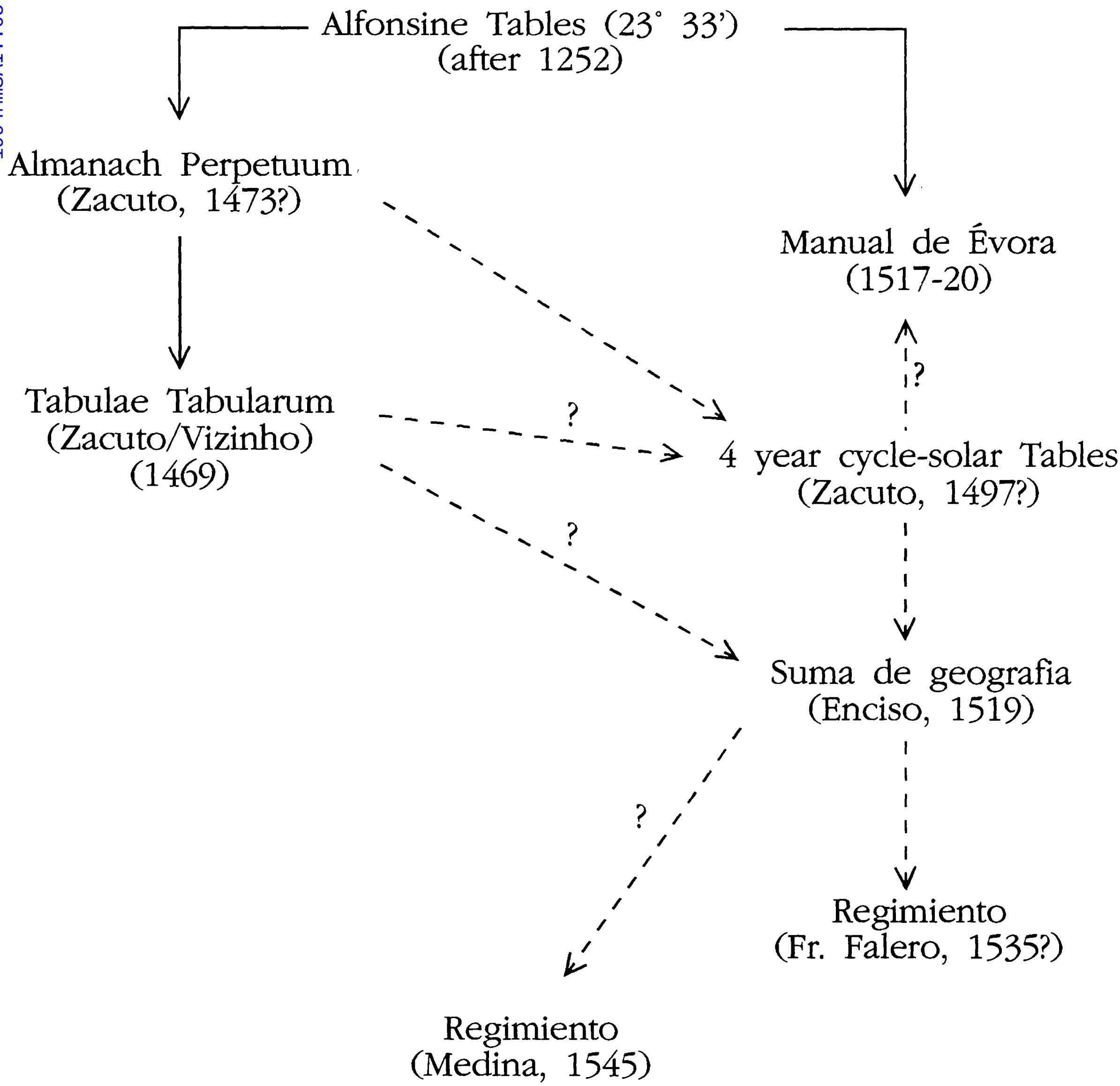

Table 2. Diagram of the probable development of nautical charts derived from the Alfonsine Tables up to the middle of the 16th century.

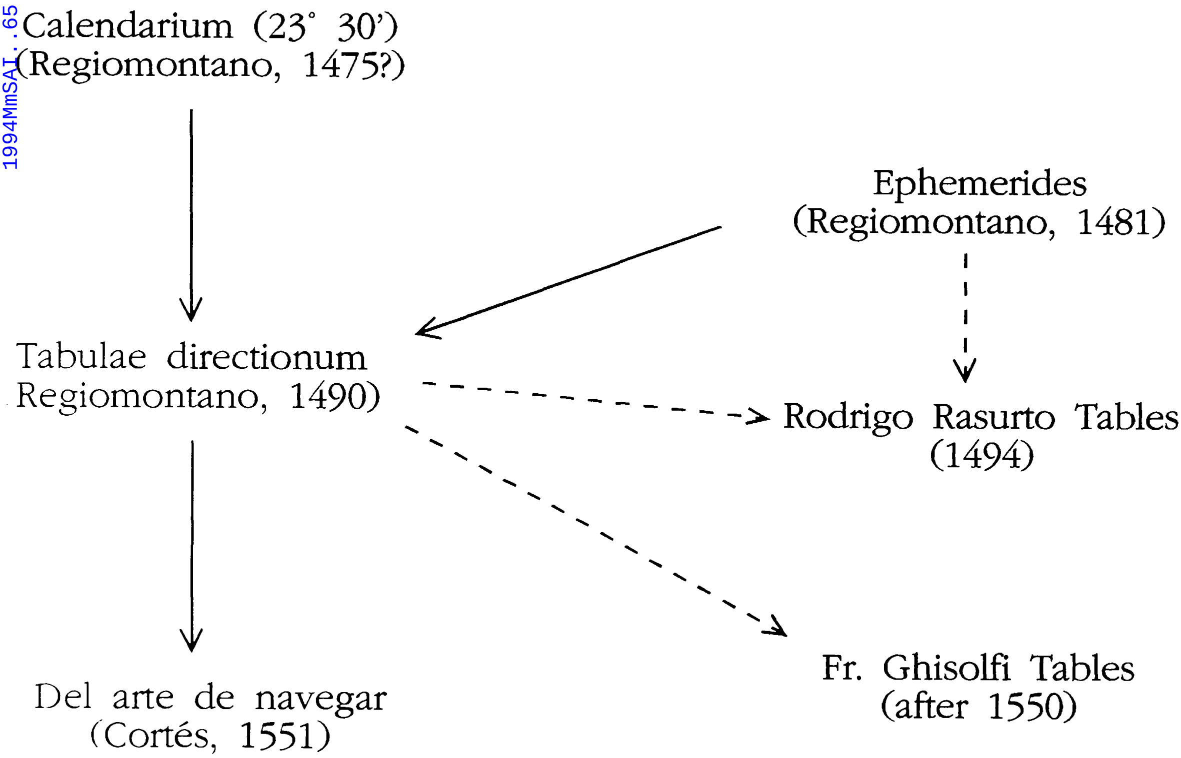

Table 3. Diagram of the development of the first nautical charts derived from Regiomontanus's "Tabulae Directionum".

Notes and Bibliographic References

(1) The beginnings of a project for the systematic exploration of the African coasts financed by Prince Henry can be dated at about 1430-32 (cf., P. Revelli, Cristoforo Colombo e la scuola cartografica genovese, Genova, 1937, Vol.II°, 282-293).

(2) On the origin and use of the term, see B. R. Motzo, compasso da navigare, Cagliari, 1947, 105-107.

(3) On literary references to the use of the Pole Star and other stars in the steering of ships, see: B. R. Motzo, ibid., 100-107.

(4) On the passage by Ramò n Lull, see: P.Revelli, op. cit. in Note (1), 412-413.

(5) Among the most ancient testimonials to the use of natural instruments in estimating latitude at sea by observation of the height of the Pole Star, we find the one supplied by Marco Polo on his return from China while navigating along the coasts of Malacca and India (1272). Similar procedures were used on voyages along the African coasts undertaken by the Venetian Alvise da Cadamosto (1455) and the Portuguese Pero da Sintra (1460)(cf., E. Proverbio, "On the instruments for the astronomical navigation in the second half of the 15th century", Proc. of the Inter. Symp. on "Tiempo y Astronomia en el encuentro de los Mundos", Varsavia-Frombork, 1992 (in press).

(6) Ptolemy, in the Almagesto, translated from Arabic to Latin towards the middle of the 12th century by Gherardo da Cremona (c. 1114-1187), had already produced a table for calculating the duration of the day at the summer solstice (longitudo longioris diei) as a function of latitude. This was later used by some medieval authors.

(7) Cf., Diego Gomes, "As relaçoes do descubrimento da Guiné e das Ilhas dos Açores, Madera e Cabo Verde", version from Latin by Gabriel Perreira, Boletin de la Soc. de. Geogr. de Lisboa, 1898-99, N° 5, Lisboa, 1900, .

(8) Cf., Libros del saber de Astronomia, del rey D. Alfonso X de Castilla, edited by D. Manuel Rico y Sinobas, Madrid, 1866, Tomo IV° Cap. XXXVIII, .168

(9) The altitude of the pole of rotation, that is, astronomical latitude, φ differs only slightly from altitude assumed by the Pole Star (α UMi) at the epoch of the maximum western and eastern degressions. Having: $\sin h_M = \sin \varphi$ $\operatorname{cosec} \delta$, it can easily be shown (for δ = 3°.5 about) that the difference remains lower than 10' up to latitudes of 60°.

(10) On the controversial determination of latitudes by Christopher Columbus at the time of his third voyage, see: A. Magnaghi, "I presunti errori che vengono attribuiti a Colombo nella determinazione delle latitudini,. Boll. R. Soc. Geogr. Ital., vol. LXIV, 1928, 473-479 and 486-490.

(11) A brief, but useful description of the Regimento do Astrolabio e do Quadrante is to be found in: E. G. R. Taylor, Haven-Finding Art, London, 1962, 162-166.

(12) The passage of the equator was accomplished in 1471 by Joao de Santarém and Pero de Escobar, the discoverers of the Island of Annobon (cf., Revelli, . in Note (1), 292).

(13) A fourth case in the measuring of latitude at sea was illustrated for the first time by John Davis in his Seaman's Secret (1594), at very high latitudes when the Sun is low on the horizon and to the north of Zenith and Pole. This method was followed by William Barents in 1594 on his voyage to the arctic regions (cf., J. B. Hewson, A History of the practice of Navigation, Glasgow, 1983, 110).

(14) Of (at least) one of Columbus's voyages from Lisbon to Guinea at the time of his sojourn in Portugal, we have documentation in the well-known postilla to the Imago Mundi by Pierre d'Aylli, printed in Leuven probably in 1483, written by Columbus himself (cf., Revelli, op. cit. in Note (1), 142-143). Indirect documentation of one of Columbus's voyages to Guinea may also be desumed from his mentions of Guinea in various circumstances, as if he had actually stayed there for some time. In the "Giornale di viaggio", dated October 1492, on describing the flora of the island of Hispaniola (Haiti), he mentions a "gran cantidad de palmas, de otra manera que las de Guinea y de las nuestras". And, concerning the language of the inhabitants of the Antilles, he notes (12 November 1492): "todos se intienden... lo que non han en Guinea, adonde es mil maneras de languas, quela una no entiendre la otra" (cf., Raccolta di documenti e studi pubblicati dalla R. Comm. Colombiana, Roma, 1893. Parte I^, Vol. I°). And, once again, in postilla 234 to the same Imago Mundi, Columbus also states explicitly: "E sotto la linea equinoziale dove i giorni sono di dodici ore, il serenissimo re di Portogallo ha un forte (la "Mina", in Guinea) nel quale sono stato e trovai che il luogo era temperato".

(15) The Jew Master Josephus, who later changed his name to Josè Visinho, was a disciple of the astronomer Abraham Zacuto, whose work Tabulae tabularum coelestium motuum, etc., Leiria, 1496, he translated from Hebrew into Latin. In Columbus's testimony (postilla 860 to the Historia rerum ubique gestarum, by Enea Silvio Piccolomini, printed in Venice in 1477), "Magister Josepium" performed latitude observations based on the Sun's height in Guinea in 1485, acting upon orders from John II, King of Portugal from 1481 to 1495 (cf., Revelli, ibid. 16 and 142). On events connected with these observations by M. Josephius refer to: A. Magnaghi, op. cit. in Note (10), 459-480.

(16) On latitude observations with the elevation of the Sun at noon carried out by Bartolomeo Diaz, refer to the following source: E. Poulle, Les conditions de la astronomique au XV° siecle, "Agrupamento de estudos de cartografia antiga, XXX, Coimbra, 1969, 3.

(17) For sources relating to latitude observations during voyages up to the middle of the 16th century, refer to: E. Proverbio, op. cit. in Note (5).

(18) Giovanni Bianchini, Georg von Peuerbach's master, was the first of the series of Italian compilers of almanacs. His Tabularum canones, calculated for the city of Ferrara, were published for the first time in Venice in 1495. Two other editions followed in 1526 e 1553.

(19) Johann Müller, known as Regiomontanus, was a pupil of Peuerbach's. As a member of Cardinal Bessarione's entourage, he visited Italy and cooperated in work on the reform of the calendar upon the invitation of Pope Sixtus IV. He was an acute observer. His series of observations of the Sun's meridian altitudes, from which another value for the obliquity of the ecliptic was derived, were important. Some time around 1474 he published (Nuernberg) a Calendarium, in which he indicated the dates of eclipses for the years 1475-1530. The Ephemerides (1482-1506) appeared in the Ratdolt editions in 1481. The first edition of the Tabulae directionum (Auguste Vindelicarum) appeared instead in 1490, and the work Epitoma J. De Monte regio in almagestum Ptolomei (Venetiis) was published in 1496.

(20) The Jew Abraham Zacuto (1452? -1522?) taught astronomy at the University of Salamanca in Spain from 1473 to 1478, where he wrote in Hebrew the Almanach Perpetuum. With the beginning of the anti-Jewish policy inaugurated (1492) by the Spanish king, Zacuto fled to Portugal, where he became a consultant to King Emanuel who, upon the death of his cousin John II (1495), gave new impulse to the improvement of latitude navigation techniques (cf., D. W. Waters, "Science and the Techniques of Navigation in the Renaissance", in: Art, Science and History in the Renaissance, Baltimore, 1967, 208-210).

(21) On the structure of the "tavole astronomiche" and the "tavole del primo mobile" in the Lower Middle Ages and the Renaissance, see: E. Poulle, Les sources astronomiques (textes, tables, instruments), Inst. d'Études Médiévales, Fasc. 39, Louvain, 1981.

(22) The Tavole Toletane, referring to the meridian of Toledo, are a collection of astronomical data compiled by the Arab Ibraim abu Ishak (1080), known as al-Zarqali o Arzachiel, who appears to have been born in Cordova, and lived between 1029 and 1087 about (cf., J.. Delambre, Histoire de l'astronomie du Moyen Age, Paris, 1819, 176).

(23) On the initiative of Alfonso X of Castille, the Alfonsine Tables were drawn up by a group of Jewish, Christian and Arab astronomers under the direction of the Jew Ishac ibn Sid ha-Hazzan and Yehuda ben Moshes in the period between 1252 and 1272 (cf.,A. Wegener, Die Astronomischen Tafeln, Inaugural Dissertation, Friedrich-Wilhelms Univ., Berlin,1905). The first Latin edition is: Alfonsii regio ...coelesti motum tabulae, Venetiis, 1483. The treatise: Libros del saber de astronomia, (Note (8)) was associated with the AlfonsineTables.

(24) In Book I, chap. XXXIV, 186-187 of the Libros del Saber Astronomia, cit. in Note (8), we find: "Et en la cabeça de cancer et en cabeça de capricornio fallaras mayor declinacion que en ninguno de los otros grados, que en cada uno destos logares fallaras la declinacion XXIII grados et XXXIII menudos et en cada un grado de los otros grados del zodiaco fallaras la declinacion menor desta quenta".

(25) In the introductive dedication to his Tables, Regiomontanus wrote: "Tantum igit utilitatem proesul dignissime directionum tabulae afferent, quas potebas, in quacunque regione latitudinem 60 graduum excedente, sive significatur dirigendus in itinere solari existat, sive ab eo versus alterum polorum secedat, in quibus maximam ab Aequatore supposuit declinationem trium et vigenti graduum cum dimidio, observationibus modernis maiorem non admittendibus", (cfr., Joannis de Monteregio, clarissimi, Tabulae Directionum, etc., Witebergae, 1584).

26) The value of 23°33'30 for Arzachiel's Table is the one proposed by E. Poulle (cfr., Les conditions de navigation astronomique au XV° siecle, Agrup. de Estudos de Cartographia Antiga, XXVII, Coimbra, 1969).

(27) Cf., A. M. Cesari, Il trattato della Sfera di Andalò di Negro, Milano 1982. In Chapter IX of the Tractatus (Capitulum de Circulis Sphaerae), we find: "Imaginati sunt etiam in coluro cancri ex parte poli artici punctum g, i distaret ab aequinoctiali per gradus 23, minuta 33, secunda 30; quia tanta est declinatio solis ab aequinoctiali, licet ponatur in Almagesto, libro I, Cap. 13 dictam declinationem esse gr. 23, min. 51, sec. 20". Similar references are to be found in the same chapter and in Chapters IX and XIV.

(28) In the Table of the horae diei longioris contained in the Tractatus Sphaerae, which follows the one given in the Dictio Secunda of the Ptolemaic Almagesto (cf., P. Liechtenstein, Almagestum Cl.Tolomei, Venezia, 1515), the values given for the duration of the day, at least up to latitudes of 60°, satisfy fairly well the Ptolemaic obliquity values . For latitudes above 61 degrees this condition is no longer respected. For example, the 21-hour length of the day presumed for latitude 64° corresponds to an obliquity of 24°15'!

(29) On James of Majorca see: Gouçal de Reparaz-fill, Mestre Jacome de Malhorca, Coimbra, 1930.

(30) Cf., P. Revelli, op. cit. in Note (1), 307-308, 311; E. G. Taylor, op. cit. in Note (11), 197; M. Duflot de Mofras, Recherches sur les progrès de l'astronomie e des sciences nautiques en Espagne, Paris, 1839, 8.

(31) Upon the death of John I, who reigned in Portugal from 1385 to 1433, his eldest son Edward (1391-1438) ascended the throne and, following his brief reign, the latter's son, Alfonso V (1392-1481) succeeded to him, under the regency of his uncle, Peter (1392-1449) from 1438 to 1449.

32) Cf., Barros, Do Asia, Lisbona, 1562, Decade I, Libro 4, Cap. II. Navarrete, to clarify the quote by Barros, commented: "trata Barros del modo de navegar que tenian los portugueses en los premieros años de sus descubimientos, siguendo sempre la direction de la carta de Africa, que nunca perdian de vista, i de la necesidad en que alguna vez se vieron de abandouarla, engolfandose en el mar; por cuxa razon pensaron en aplicar las observaciones astronomicas para correger los errores de la estima. Con esto objeto el rey D. Juan II formo una junta de matematicos, compuesta de sus dos medicos, maestre Rodrigo y maestre Josef, indio, y de Martin de Behem, que estableceron el metodo de navegar par la altura del Sol, y formaron las tablas de su declinaciones (cf., Colecion de los viajes y descubibimiento que hicieron par mar los espagnoles, etc., par don Martin Fernandez de Navarrete, Madrid, 1858, Tomo I).

E. G. Taylor and D. W. Waters appear to accept the thesis whereby the "junta" was made up of: Master Rodrigo, Master Josephus (Jose Vizinho) and Diego Ortiz according to Taylor (op. cit. in Note (11), 162); of: Jose Vizinho, Martin Behem e Diego Ortiz acccording to Waters (op. cit. in Note (20), 207). Barros refers to a committee or "junta" composed of Master Josephus, Diego Ortiz and Master Rodrigo, which expressed an unfavourable opinion on Columbus' project (cf., Barros, ibid., Decade I, Libro 3, Cap. IX). This "junta", which appears to be the same one mentioned by Taylor, must have been at work at the time of Columbus' sojourn in Portugal (1479-84). Waters seems to accept the date of 1483 for the meeting of the "junta" that rejected Columbus' project (cf., Waters, ibid., 207).

(33) In 1492, Martin de Behem from Nuremberg (a disciple of Regiomontanus'?), after his temporary return home, built a famed terrestrial globe of metal, with the first meridian passing through the Canary Islands. It is most probable that Martin de Behem, in constructing his globe, used to good advantage the information he had gathered during his voyages along the African coast with Diego Câo (1484-85). In the opinion of D. W. Waters, Behem built his globe to persuade the rich merchants of Nuremberg to participate financially in the explorations of the Portuguese navigators, thus gaining commercial advantages (cf., op. cit., in Note (20), 207). On Behem's disputable training in astronomy, see Magnaghi's considerations, op. cit. in Note (10), 475, Note 5.

(34) On the date on which the "junta" was appointed, presumably by John II, who succeeded King Alfonso V in 1481, available sources and information are in disagreement. Waters (ibid., 205-207) places the constitution of the "junta" in 1485, while Palomeque Torre states that: "En Portugal su rey Juan II en 1480 convocó y organizó una Junta dos mathematicos con los maestres Rodrigoy Josef, sus medicos y Martin Behaim, etc.", (cf., A. Palomeque Torres, "Ambiente politico y cientifico que rodeó al futuro Almirante de Indias D. Cristobal Colon en la España de los Reyes Católicos", in: Studi Colombiani, Genova, 1951, vol. II, 348).

(35) The cosmographer Diego Ortiz, professor of astrology at the University of Salamanca starting from 1469, was forced to leave Spain for political reasons in 1475. He took refuge in Portugal, entered the service of King Alfonso V and later served John II.

(36) Cf., Note (20).

(37) The conjecture that the Regimento goes back to "rules" written some time around 1480-81 is based on the fact that in the list of latitudes given in the manual we find equatorial latitudes of sites reached in oceanic navigation in about the same period of time (cf., Taylor, op. cit. in Note (11), 162). Beaujouan propends for a later date (about 1483) for the preparation of a first draft of the "rules" (cf., G. Beaujouan, Science Livresque et Art Nautique au XV Siécle, Paris-Lisbonne, 1960, 20).

(38) Cf., Taylor ibid., 162.

(39) A fac-simile edition of this rare manual is to be found in the series edited by J. Beusaude cited by Taylor (ibid., 203).

(40) A first element that differentiates these early navigation tables from the medieval astronomical tables (Alfonsine and Toledan) is the fact that in the latter the position and declination of the Sun are usually given as a function of the degrees of the zodiac. It can be imagined that the calculation of the Sun's declination by pilots on the various days of the year, starting from the Sun's longitude, should certainly have discouraged, more than it actually did, the use of the new navigation techniques.

(41) This rule, called the Regimento dos rumbos, where *rumbo* (in English *rhumb*) is synonymous with one of the directions of the wind rose (even today in Portuguese *rumbear* means to pilot a ship), thus allowed, with the given value m_i of the distance in leagues corresponding to a variation of 1° of latitude in one of the eight directions A_i ($i \approx 1, ..., 8$) of the wind rose, the calculation of distance d_i the course followed in the given direction. The calculation was performed on the basis of the relation $d_i = m_i (\varphi_A - \varphi_B)$ where $\varphi_A - \varphi_B$ was the variation in latitude corresponding to extremities A and B of the course travelled. From quantity m_i measured experimentally, it was instead possible to deduce the so-called module of degree m (number of miles contained in a degree). Up to the introduction of spherical maps, the module of 17½ leagues (equivalent to 70 miles) used by the Portuguese as the measurement of 1° thus appears to have been derived from the measurement of distance as a function of latitude performed while sailing the high seas,by means of the relation: $m = m_i \cos A_i$ (this hypothesis is suggested by Waters in op. cit. in Note (20), 206 Note 10). On the modules of the degree used by Portuguese and Spanish navigators in the 15th and 16th centuries, see: G. Uzielli, "La vita e i tempi di Paolo dal Pozzo Toscanelli", in: Raccolta di documenti, etc., .in Note (14), parte III^, 409-428.

(42) On the technique for steering known as the martelojo, see: Enrico A. D'Albertis, Raccolta di documenti, etc., ibid., Parte IV^, vol. I, - 117-155.

(43) On the question of the date of publication of Évora's Manual, see the considerations by E. Poulle (cfr., op. cit. in Note (26), 13.

(44)., E. Poulle, ibid., 12-16.

(45) That the Munich tables had been derived directly from Zacuto's Almanach Perpetuum, and thus from the Alfonsine Tables from which the latter originated, is explicitly stated byTaylor and Waters (cf., op. cit. in Notes (11), 165 and (20), 206).

(46) The table of the day's length at the solstices as a function of latitude and the table of the Sun's declination as a function of the degrees of the zodiac (see Note 40), drawn up by Columbus, are given in the first postilla to the "Ymago mundi" by Pierre d'Ailly (cf., Raccolta di documenti, cit. in Note (14), Parte I, vol. III). The declination of the Sun relative to degree 90 of signs 3 (Cancer) and 9 (Capricorn) is indicated as 23°33', which may suggest that it derives from the Alfonsine Tables. The approximation in primes of arc with which many medieval compilers of almanacs indicated the Sun's declination still represents an element of uncertainty in establishing the sources from which these authors derived their almanacs. For the length of the day at the summer solstice, Columbus supplied the value of 22^h and 27^m for the latitude of 66°. The calculation of this duration, using the value of 23°33' for the Sun's declination, gives $22^h25^m.8$. If instead we start from the value of 23°33'30;" we have for duration the value $22^h25^m.8$. It is to the latter value, and therefore to the obliquity given by Arzachiel's Tables, that Columbus presumably referred in calculating his table of the length of the day.

(47) The information is taken from Waters, op. cit. in Note (20), 210.

(48) In his Armados dos Alboquerques que passarão á India, o ano de 1503, Gaspar Correa reports: "...todas estas armadas ...navegando polo regimento (astronomical rule or table) que dera o judeu Çacuto, que jà os pilotos tinhão experimentado, etc." (cf., Waters, ibid., 210).

(49) For an ample documentation concerning the activities of the Spanish throne to favour the development and application of practical and theoretical knowledge on new sailing techniques and the organization of the Casa de Contratacion, see the five volumes of the work by Navarrete, cit. in Note (32).

(50) Cf., J. Pulido Rubio, El Piloto Mayor de la Casa de Contratacion de Sevilla, etc., Sevilla, 1950.

(51) In 1519, the office of "Maestro de Hacér Cartas" was created at the Casa de Contratacion, and in 1523, that of "Cosmografo Maestro de Hacér Cartas, astrolabios y otros ingenios de navegacíon" (cf., Waters, cit. in Note (20), 213) was also set up).

(52) Cf., Fernandéz de Enciso, Suma de geographia que trata de todas las partidas y provincias del mundo, etc., Sevilla, 1509. Two further editions of this work appeared in 1530, and a fourth in 1546.

(53) In the work cited in Note (20), Waters, referring to Enciso's Suma de geographia, specifies: "It was published by Juan Cromberger at Seville in 1519, with solar declination tables prepared originally for Vasco da Gama for the four-year cycle 1497-1500". It appears, however, that for the existence of the latter tables we have only the indirect testimony supplied by Gaspar Correa.

(54) Cf., Francisco Faleiro, Tratado del Esphera y del arte del marear: con el regimiénto de las alturas: co alguas reglas escritas muy necessarias, Seville, 1535. In a recent edition prepared by J. Bensaúde (Bern and Munich, 1915).

(55) Regimiento de navigacion, etc., fecho por el maestro Pedro de Medina, Sevilla, 1545.

(56) Cf., L'art de Naviguer de maestre Pierre de Medina, etc., traduit de castillan en français, etc., par Nicolas de Nicolai, du Dauphinè, etc., Lyon, 1554.

(57) See Note (28).

(58) Cf., Martin Cortès, Breve compendio de la sphera y de la arte de navigar, Seville, 1551. A second edition followed in 1556.

(59) Cf., Revelli, op. cit. in Note (1), 407-408, Tav. 65.

(60) Cf., Palomeque Torres, op. cit. in Note (34), 348.