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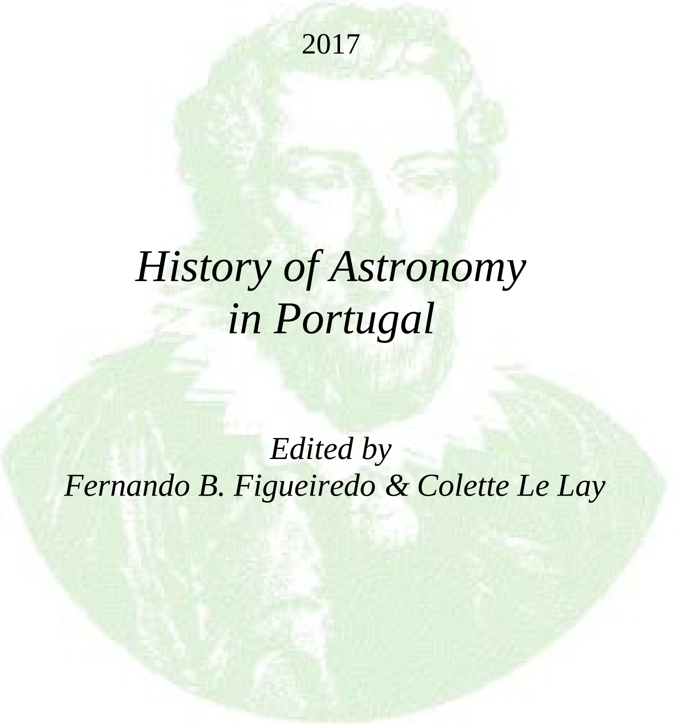

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in Portugal

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The Astronomical Navigation in Portugal in the Age of Discoveries

António Costa Canas[*]

Abstract

This paper is about the evolution of astronomical navigation in Portugal, in the Age of Discoveries. We will focus our attention on the contributions, by the Portuguese mariners, to the determination of latitude at sea, using Polaris or the Sun. Besides the longitude issue has a solution only in the second half of 18th century, the Portuguese sailors intended a method to obtain this geographical coordinate, appealing to the conjunctions and oppositions of the Moon. This method was used in Magellan's voyage (1519-1522). In this paper, we will try to present these efforts made by the Portuguese, that allowed them to face the vast oceanic waves with some degree of confidence.

Keywords: Portugal, discoveries, astronomical navigation, latitude, longitude, Magellan circumnavigation voyage.

Résumé

Dans ce texte nous analysons l'évolution de la navigation astronomique au Portugal, à l'époque des grandes découvertes. Les contributions des Portugais ont permis de déterminer la latitude en mer, principalement en ayant recours à l'étoile Polaire et au Soleil. De plus, la question de la longitude n'ayant de solution que dans la seconde moitié du XVIII^e siècle, les marins portugais ont cherché une méthode pour obtenir cette coordonnée géographique, utilisant les conjonctions et les oppositions de la Lune. Cette méthode a été utilisée pendant le voyage de Fernão de Magalhães (Ferdinand de Magellan, 1480-1521), 1519-1522. Dans cet article, nous tenterons de présenter ces efforts faits par les Portugais, ce qui leur a permis de faire face aux vastes ondes océaniques avec un certain degré de confiance.

Mots-clés : Portugal, découvertes, navigation astronomique, latitude, longitude, voyage de Magellan.

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THE HISTORIOGRAPHY of the Portuguese Discoveries has already more than five centuries. The set of works on the history of the Portuguese epic, in the various overseas "empires", is of great importance in technical-scientific and literary aspects.

However, it was in the 20th century that the theme was renewed in its approach and gained a new scientific and historiographic interest. This interest did not only come from the part of national researchers but also from the part of the international scientific community. It would be interesting for the reader to consult the work of João Marinho dos Santos and José Azevedo e Silva (Santos 2004), in which these authors try, through the publication and analysis of the correspondence of the main 20th century Portuguese researchers, to reconstitute and reanalyse the great scientific discussions around the theme of the Discoveries. This book also shows that the epistolary material exchanged between these historians and foreign scholars is itself a great documentary to be taken into account in future research about this subject.

Joaquim Bensaude (1859-1952), Luciano Pereira da Silva (1864-1926), Abel Fontoura da Costa (1869-1940), Gago Coutinho (1869-1959), António Barbosa (1892-1946), Avelino Teixeira da Mota (1920-1982) or Luís de Albuquerque (1917-1992), just to mention only a few of the most important authors, published hundreds of books and papers in which this subject is discussed. They published not only in Portuguese but also in some other languages.[1]

Through the impetus given by the systematic work of these men, as well as by foreign researchers, a solid historiography has been constructed, pointing out and highlighting the decisive role of Portuguese pilots and scholars in the great scientific work of the Iberian and European Discoveries made from the 15th century.

In this article, we will try to give a contextualised summary of the main contributions of the Portuguese to astronomical navigation

Astronomical Navigation: From Art to a Technique

- *The Influence of Mediterranean Techniques in the Portuguese Art of Navigation*

The majority of historians assume that the military conquest of Ceuta (1415) marks the beginning of Portuguese Expansion. This expan-

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[1] In French, we highlight the following: (Bensaude, 1912; Fontoura da Costa, 1935, 1938; Beaujouan & Poulle, 1959; Cortesão, 1966).

sion went far beyond the Moroccan territory. The Portuguese started to explore the West Coast of Africa, venturing to regions more and more distant from land and therefore losing visual contact with the coastline, discovering new islands in the Atlantic Ocean. These islands were unknown by the Europeans until then. Later, they navigated to the Indian Ocean and travelled to India by sea. In less than a century, the Portuguese established regular routes across the Atlantic Ocean and the Indian Ocean. Their main destinations were Brazil, Africa and especially East India; from where they brought many very valuable goods, especially spices. In fact, we can speak of a European expansion that changed the world forever. This expansion was led by Portugal and followed by other major powers such as Spain, England and the Netherlands. This process has entailed many changes in the 'Art of Navigation'. When the expansion started, the ancient Mediterranean navigation techniques, developed in the Mallorca and Italian coast, were not enough for the new needs raised by the open oceanic voyages which had been carried out by Portuguese and European navigators from the 16th century onwards.

We have evidence of intense maritime activity in the Mediterranean Sea thousands of years ago. The Mediterranean seafarers used to sail instinctively. As they were often of rural origin and illiterate for the most part, their culture was made up of sayings, proverbs, lived experience, but also myths and extravagant foolishness (Pastoureau, 1992).[2] Despite this, we can talk about more or less complex techniques to conduct ships safely because in the absence of these techniques navigation was impossible. One of them was the introduction, by the end of Middle Ages, of compass on board ships. We do not know who was responsible for the introduction of this innovation, or the precise moment when it happened, but by the end of the 13th century, some navigators had compasses on board ships (Albuquerque 1972, p. 16-19).

The use of compass led to the development of the navigation method known as dead reckoning. To sail from one position to another position, the pilot needed to know the direction he must follow, reading it on the compass. He also needed to know the distance he had travelled. He did not have any instruments to measure speed, so he estimated the distances. This method was suitable for the needs of the sailors in the Mediter-

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[2] On the 'Partidas' of Afonso X de Castilla (1221-1284) are described which in the 13th century was considered essential to a sailor, knowing all the sea, where it is calm, and also the "winds and their changes [...] and the entrances and exits to guide the ship safely ["os ventos e as mudanças deles [...] e as entradas e saídas, para guiar o navio a salvo"]" (Albuquerque, 1972, p. 13-14).

ranean Sea. The errors associated with this method, such as those introduced by the lack of accuracy of the compass directions, or the wrong evaluation of the travelled distance and the unknown effects of the currents could somehow be neglected since the ships never sailed too far from shore. However, these errors can be very significant if ships spend weeks or even months without sight of land. This kind of unfavourable conditions did not occur in the Mediterranean Sea. To fix positions, the sailor used nautical charts based on compass directions and distances estimated. That charts, known as portolan-charts[3], had a grid of directions, usually 32, one for each direction of the compass, and also a scale to measure distances. The oldest known chart of this kind is the "Pisan Chart", from the end of the 13th century (or from the early years of the following century). The process described above spread from the Mediterranean Sea to the Atlantic coasts of Southern Europe.

It is very likely that the Portuguese sailors knew this method and had used it in the first exploration voyages in the Western African coast. During these voyages, they never stayed away from the sight of land for long periods. In this way, the method was perfectly appropriate for them. However, when they reached the region of the South of Cape Bojador (1734), the return voyage became very difficult due to meteo-oceanographic conditions. To solve this problem, they sailed into high seas, using the prevailing winds to take them back home. They spent long periods without sight of land.[4] Soon, they realised that by using only dead reckoning errors could increase considerably. It became convenient to know the approximate position of the ship, if not at all times at least each day, during a long voyage without any land reference. To sail in the open sea, out of sight of the coast, the Portuguese conceived and developed the astronomical navigation, making astronomy the faithful auxiliary of their enterprise of discovery.

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[3] The name derives from portulano, because the information we can obtain from them is similar to the one we can get from portolans. These consist of a textual description of the paths connecting different harbours in one region. In portolans, we have information about directions and distances the pilot should follow to travel to the mentioned harbors. "Il Compasso di Navigare", dated from the middle of the 13th century, is the oldest known portolan.

[4] At the time of the Discoveries, this return was denominated "volta da Guiné" or "volta da Mina", because the ships that left Guiné or Mina moved in an arc towards the northwest, to gain the latitude of a certain point of the Portuguese coast. In modern historiography, especially after the studies of Gago Coutinho, this return is denominated "volta do largo" (Albuquerque, 1989, p. 74).

It was essential not only to travel safely in seas that had never been navigated before but also to return to the new lands that were discovered. Taking possession of new stop-over points required precise location, which could only be found in the heavenly vault. An issue is also intimately linked to the improvement of cartography.

Astronomical Navigation is opposed to navigation by esteem, but it is important to highlight that astronomical navigation did not completely replace dead reckoning, which remained the primary method to fix the position of the ship at any particular time. With astronomical navigation, the pilots were able to reduce errors resulting from the impossibility to correct positions observing landmarks. In the 16th century, the tools used by the pilots to conduct ships proved the importance of dead reckoning. The nautical charts kept the grid of directions and the scale to measure distances. Mapmakers just incorporated something else: a scale of latitude. Similarly, the routers, which replaced portolans, still had information about directions and distances from place to place. However, they incorporated lists of latitudes of places. With the Portuguese of the 15th century, Navigation passed, finally, from art to technique.

- *Astronomical Navigation*

One important contribution to the development of astronomical navigation in the Middle Ages is the fact that sailors were used to look at the sky regularly. They did not measure the altitude (the angle above the horizon) of the stars, but they observed celestial bodies to determine local time. The process was based on the observation of the relative positions of two stars: *Polaris* and *Kochab*, both from *Ursa Minor*. That meant that they observed the sky very often, especially in the direction of *Polaris*.

Used to observe the sky, Portuguese sailors noticed that the altitude of *Polaris* decreased as they travelled southward. Alvise de Cadamosto (ca. 1428-1483), a Venetian sailor who explored the African coast under the orders of Prince Henry, *the Navigator* (1394-1460), observed that. In 1456, in a local near to the mouth of Gambia river, he noticed that the star was very low: "... we saw it over the sea, at the altitude of a javelin..."[5] Of course, this is not astronomical navigation, but just the observation of the fact that the altitude of the star decreases when the ship sails to the Southern direction.

Nautical astronomy, or astronomical navigation, is based on methods and processes that allow the pilot to determine the approximate position of a ship thanks to observations of the stars. To do so, it must respond to

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[5] Le Navigazioni atlantiche di Alvise Ca da Mosto, quoted in (Albuquerque, 1975, p. 16).

three problems: determination of the latitude during the day, by the sun; determination of latitude by stars at night; and determination of the difference in longitude between two places, calculated by the differences of time in which a given celestial event is observed.

Astronomical navigation developed step by step. The oldest known reference to the use of an instrument to measure the altitude of a star at sea is from around the middle of the 15th century.

It was registered by Diogo Gomes (c. 1425 - c. 1500) who sailed under the orders of Prince Henry. Gomes said that he observed the height of the pole[6] in a position close to one island of Cape Verde archipelago, registering this value in his quadrant. If this value is known, it should be easy to return to the island. To do so, the pilot should sail southward, until he observes the star with the same altitude previously obtained. Then he just needs to travel east or west, always keeping the star at the same altitude. This process is known as: "*equal altitude of the star*".

It is important to note that despite the evolution of astronomical navigation in the following decades, the process mentioned above remained in use. The safest way to arrive at any island in the middle of the ocean was to sail until the ship reached the latitude that was parallel to the island, and then sail along the parallel until the island was found. The ship should not head directly towards the island but to a position which would be east or west of the island. Using this procedure, the pilot knew which direction he should sail when he reached the latitude of the island.

Another process developed in the first years of astronomical navigation is the one we call "*altitude-distance*". The pilot assumed that one meridian arc is equivalent to a certain number of leagues. At sea, he measured the altitude of a certain celestial body, during several days. The difference between the altitudes observed equals an arc along the meridian, and this is equivalent to the distance travelled north or south. It was necessary to observe the star in similar conditions, which was more or less equivalent to observe it at the same time during both days. Even in the case of *Polaris*, whose height changed just a little amount of time, the fact that it was observed in different conditions from one day to the other could cause large errors in the distance calculated.

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[6] In fact, he probably registered the altitude of *Polaris*. Despite the fact that the star is very close to the North Pole, its altitude changes with time. For a given place, the difference between the highest and the lowest value is not negligible. To overcome this inconvenience, the altitude should be measured with the star always in the same position. It was not difficult to do so, due to the fact that Portuguese sailors observed *Polaris* very often.

We must fully take into account the fact that the notion of latitude is not present in any of the processes mentioned above. In the first one, the pilot just needed to know the altitude of one star, *Polaris*. When he reached this altitude, he sailed east or west, keeping the star with that altitude. Because the trajectory of the star described a small circle around the North Pole, its altitude varied during the night, even for an observer in a precise location. It was easy for the pilots to know the altitude values according to the different positions of the star around the pole; they just needed to observe the relative position between *Polaris* and *Kochab*, as they used to do to find out the time during the night.

In some of the oldest navigation books such as *Guia Náutico de Munique (c. 1509)*, *Guia Náutico de Évora (1516)*, or *Repertório dos Tempos (1518)*[7] by Valentim Fernandes (?- c.1518) there are diagrams showing eight values for the altitude of *Polaris* in Lisbon.

This kind of texts had more or less simple nautical instructions to be used by pilots. Most of the pilots of this time were men of little, or none, theoretical instruction. Thus, these manuals provided technical and scientific information considered useful, but the truth is that many of these men had serious difficulties in understanding the true meaning of these rules and procedures. For example, Pedro Nunes wrote some books solving certain navigation problems, but these texts were essentially theoretical and therefore virtually inaccessible to seafarers.[8]

The *Guia Náutico de Munique* (Munich Regiment, or Nautical Guide of Munich), is the oldest book known and printed with nautical rules. It was published in the workshop of Hermão de Campos in Lisbon, probably in 1509 and reprinted c.1516. The Munich Regiment includes a translation of the *Treaty of the Sphere* of Sacrobosco, through which many generations of pilots learned the rudiments of cosmography; two versions of the r*egiment* for determining the latitude from the meridian height of the Sun and its declination; a table with sun declinations; the regiment for the determination of latitude by the height of the Polar Star; a wheel with the heights of the Polar star in Lisbon. In the Munich Regiment, there is also a letter addressed by a "German doctor" to the King D. João II (1455-1495), translated by Álvaro da Torre. In this letter, dating back to 14 July 1493, Jerome Monetary or Münzer, the "German doctor", praises the Portuguese

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[7] Published by Pablo Harus in Saragoça, in 1492; was translated to Portuguese by Valentim Fernandes in 1518 (Leitão & Martins, 2004, p. 36).

[8] See the article of Bruno Almeida in this volume.

king for the discoveries and instils him the way to the west to reach India more easily.[9]

In the following figure is reproduced the diagram “Polaris Wheel”, by Valentim Fernandes.

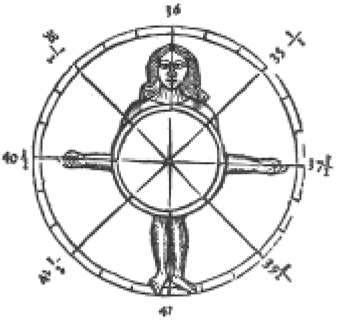

Figure 1 - Diagram “Polaris Wheel” (Source: Valentim Fernandes, “Reportorio dos tempos”*, Lisboa, Valentim Fernandes Alemão, 1518)*

The method explained in the previous paragraph was not user-friendly because there was the need for one diagram for each place that the pilot wanted to visit. The next step consisted in a small transformation of the diagram to allow its use for any place. To do so, the altitude values in the wheel should be replaced by the correction to apply to the observed altitude, to calculate the altitude of the pole. With this small change, it was easy for the pilot to calculate the latitude because it was equivalent to the altitude of the pole. This set of rules was known as *Regimento do Norte* (Regiment of the North Pole). They consisted of very simple rules, a set of numbers which should be added or subtracted to the value measured with one instrument, the star altitude, to obtain the latitude of the place.

The use of *Polaris* to obtain latitude was common to a wide community. There are examples of *Regimento do Norte* in almost all the texts about navigation from the 16th century and a large number from the 17th century. However, if Polaris was suitable for northern hemisphere, it was not for the southern hemisphere because it disappeared when a ship crossed the equator. In the southern hemisphere, there is no star as close to the South Pole as *Polaris* is close to the North Pole. Nevertheless, some pilots

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[9] This lettter can be found in (Montaro, 1878).

used a set of rules similar to the *Regimento do Norte*, to be used with one of the stars of *Southern Cross*. Because this constellation was at a reasonable distance from the South Pole, this *Regimento* had serious flaws. For this reason, its use was not as wide as the *Regimento do Norte*.

There is a celestial body which can be observed all over the year, in both hemispheres: the Sun.[10] The astronomers modified some rules, used in land, to allow the use of Sun at sea, to obtain latitude. They call these rules *Regimento do Sol*, and they consist of a set of mnemonics to help pilots to perform calculations so they can obtain the latitude while measuring the altitude of the Sun (Roche, 1981; Sonar, 2010). The rules from *Regimento do Sol* were different from those from *Regimento do Norte*. In the *Regimento do Sol* the calculations were more complex because there was the need to cover all possible situations of the relative positioning of the Sun, celestial equator and the zenith of the observer. Despite this bigger complexity, the calculations remained additions and subtractions.

The Sun rises every day in the horizon, ascending into the sky until it reaches the highest altitude, in the middle of the day, then descending to disappear below the horizon. In its meridian transit, the highest altitude is reached when the Sun crosses the meridian, exactly south from our position.[11] The altitude at meridian transit changes slightly day by day, being affected by the latitude of the observer and the angle between the Sun and the celestial equator. This last angle is known as the declination of the Sun and changes with time, on a yearly basis. In this way, since there is a numerical relation among the three factors – latitude, the declination of the Sun and highest altitude of the Sun – it is easy to calculate one when you already know two of them. With an instrument to measure the altitude of the Sun, usually a mariner's astrolabe, the pilot just needs to know the declination of the Sun for each day. With those two figures and the fact that he applies the correct rule from the *Regimento do Sol,* the pilot can calculate the latitude of the place. As we said before, the correct rule depends on the relative position among the equator, the Sun and the observer's vertical.

The process to obtain latitude using the meridian transit of the Sun was used by astronomers long before the beginning of Portuguese discoveries. The Portuguese simplified these complex calculations by making them

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[10] In fact, for very high latitudes, above polar circle, the Sun is not visible for all the days of the year. However, Portuguese ships did not reach those latitudes.

[11] This is always true for an observer in Europe. An observer between tropics can observe it sometimes to North, other times to South, and can even observe it exactly above its head. In the region of the South of Capricorn Tropic, the highest altitude of the Sun will always occur to the North of the observer.

easy enough to be executed by sailors, usually men with little school education. That was one of the most important contributions from Portugal to the development of the Art of Navigation in the 15th century.

In the last decades of the 15th century, some astronomers, like José Vizinho, sailed to the western coast of Africa, where they observed meridian transits of the Sun to obtain the latitude of many places. These expeditions also served as a test of the method. In all this process, the astronomers played a very important role, not only in teaching pilots the rules of the *Regimento do Sol* but also in preparing the tables with the daily value of the declination of the Sun, which changes day by day, on an annual basis, to be used by that same pilots.[12]

As we told before, to calculate latitude, the pilot must measure the altitude of the Sun and once again, the Portuguese simplified one instrument used by astronomers for a long time to adapt it in order to be used by sailors. Astronomers used planispheric astrolabes to perform complex astronomical calculations. This instrument had a scale to measure the altitude of stars. To do so, the user just needed to move the "alidade" towards the direction of the sunbeam to obtain the altitude in the scale. The mariner's astrolabe, also called sea astrolabe, is the simplification of that instrument made by Portuguese, removing everything useless to unlettered sailors and only leaving the scale and the alidade to obtain altitude of stars.

Portuguese mariner's astrolabes had one peculiarity that helped a lot the process to calculate latitude. To apply the rules from *Regimento do Sol,* the pilot had to convert the altitude of the star to zenithal distance.[13] To do this, he just needed to perform a very simple calculation because the zenithal distance is the complementary angle of altitude (zenithal distance is obtained subtracting the altitude from 90º). However, to avoid one supplementary operation, Portuguese mariner's astrolabes were graduated in the zenithal distance and not in altitude. With this simple modification in the astrolabe, it was possible, to make the use of the *Regimento do Sol* simpler by removing one operation. Figure 2 shows the scale from a Portuguese mariner's astrolabe, with 0º on top, to measure the angle starting at zenith.

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[12] The astronomers usually prepare tables for a cycle of four years, three common and one leap year because one year doesn't match an exact number of days, there is the need to have one extra day every four years. Strictly speaking, at the end of a four-year cycle, the Sun's position was not exactly the same position than the Sun is in the beginning of the cycle. However, the difference is so small that pilots could use the same tables during some cycles.

[13] We measure altitude starting at the horizon and zenithal distance starting at our vertical.

Figure 2 - Astrolabe São Julião III
(Source: Portuguese Maritime Museum, IN-II-174)

The oldest registered determination of latitude using the meridian altitude of the Sun, dated from the 15th century. In the first voyage of Vasco da Gama (1497-1499), the latitude of Saint Helena Bay (nowadays in South Africa) was calculated using this method. The pilot went ashore and used big mariner's astrolabes, made of wood and suspended from a tripod. But the same chronicler, who described this operation, tells us that they also had smaller brass astrolabes to be used onboard (Ravenstein, 1898, p. 167). Because they had little practice with this method, they preferred to make the observations ashore.

Longitude in Magellan's Voyage

By the end of the 15th century, the question of determining the latitude at sea was, as we described, no longer a problem. But different challenges appeared concerning longitude. At that time, some authors believed that the longitude problem was so complex that it was not worth finding a solution for it. That is the case of Duarte Pacheco Pereira (c. 1460-1533), who, at the beginning of 16th century wrote:

> […] and you must know that to measure the world width we must count the degrees from equinoctial towards each one of the poles, and how many degrees each pole rises over the horizon, which we can also call circle of the hemisphere. These same degrees are any place or man, standing there, distant from equinoctial line, and we measure the degrees of length, from Orient to Occident, that sailors denominate east and west, and because it is very difficult to calculate, because we don't have any fixed point, such as the pole to calculate width, I shall not talk about it anymore. (Pereira, 1991, p. 555)

However, some years after Pereira had written this, an event occurred, which made the determination of longitude a relevant issue.[14] In 1519, Magellan started his voyage, which would be the first circumnavigation. Magellan intended to prove that the Moluccas were placed in the Spanish hemisphere, defined by the *Treaty of Tordesillas* (1494). Magellan had never made plans to circumnavigate the globe. The obligation to navigate in waters where Spanish ships could sail explained his option to search for passage in South America from Atlantic to the Pacific Ocean. Navigation in the Indian Ocean was forbidden to Spaniards. For this reason, the return from the Moluccas was to be done by the reverse route. When the remaining ships of the fleet arrived at that archipelago, the sailors decided to come backcrossing the Indian Ocean. They chose to do that because some of the pilots had already sailed in the Eastern Indian Ocean before, whereas the route across Pacific was completely unknown.

Because Magellan wanted to prove the Moluccas were in the Spanish hemisphere, he needed to obtain the longitude of these islands. He asked the Portuguese cosmographer and astronomer Rui Faleiro (149?-?) to help him. Faleiro went to Spain with his brother Francisco, also a cosmographer, because they had problems with the Portuguese authorities – the same reason justifies the departure of Magellan. Rui Faleiro was one of the closest collaborators to Magellan in the preparation of the voyage. The cosmographer participated in the negotiations – conducted by Magellan – with Charles I (1500-1558).[15] They were supposed to participate in the voyage with the same rank: captain-general. However, Faleiro was dismissed from the project, for health reasons, because he started to present mental disorders (Mota, 1975, p. 317-318). Faleiro promised to Magellan one *Regimento* with procedures to calculate longitude. When he was dismissed from the project, Magellan asked Faleiro to give him the *Regimento* that he had prepared to obtain that coordinate. Faleiro acceded and suggested several methods and Magellan used one of them during the voyage.

The *"Regimento da altura de leste-oeste"*, a document that lies in Seville, is probably that text from Rui Faleiro (Mota, 1953, p. 910). In this text, the author proposed three methods to calculate longitude: (1) thanks to the latitude of the Moon, (2) thanks to conjunctions and oppositions of the Moon with stars and thanks to (3) magnetic variation. This last one was

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[14] About the Portuguese and Spanish attempts to measure longitude in the 16th century, see (Randles, 1985).

[15] Charles I (1500-1558) of Spain, the famous Emperor Charles V, of the Holy Roman Empire.

very popular during the 16th century, although it was based on an incorrect proposition. The method of determining longitude by magnetic variation (or magnetic declination), suggested by João de Lisbon (? -1525) in his *Tratado da Agulha de Marear* (1514), is based on the fact that the magnetic declination seems to vary regularly with the longitude on the surface of the Earth. The magnetic compass needle points to the magnetic north, which does not coincide with the geographic north, the magnetic declination thus measures the difference between these two directions. For many years it was mistakenly thought that there was a law for magnetic declination, which would thus allow knowing the true direction of the geographic north and consequently the longitude of a place.

Regarding the first one, where Faleiro proposed the determination of longitude by the astronomical latitude of the Moon, the explanation in the text is very poor. Furthermore, as Mota observed, the daily variation of this coordinate was so small that it was not possible to measure this kind of variation using instruments available at that time (Mota, 1953, p. 146).

Faleiro's proposal for the second method is, in his words, the following:

> §4 by the conjunction which I know that the moon will have with some of the fixed stars at a given moment in Seville, and which may be known by any almanack, or also by the oppositions of the Moon that is opposite to the Sun. I can teach you at what time that opposition occurs earlier to the West, and you will be to West of Seville the same amount of time. This calculation is also very useful for those who sail for the West, and it is easy to calculate.
> §5 I will give you here an example. You should believe me, the Moon moves with a retrograde motion, relative to the sky, from West to East, with an average movement of about 13 degrees [per day]. And, for a better understanding, you should know the Moon is in the first sky, and the stars are in the eighth, and the Moon never joins the stars, because it is so big the distance from the Moon to the stars. We say that we have a Moon opposition to one star when the Moon put on our visual beam in the direction of the fixed star. That doesn't happen at the same time to those who are in Seville and to those who are in Valencia. You can check it in the figure[16]; for those who are in Seville, the visual beam is a: and for them, the visual beam to Valencia is u, and presupposed this, the amount Moon moves from West to the East, it moves in two hours, one degree and a few minutes, but sometimes the Moons conjunction with the star occurs before in Seville

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[16] In the text of Faleiro, there is no figure but everything that follows his description presupposes that there was a diagram where the lines of vision of the two observers, one in Seville (a) and another in Valencia (u), were marked.

> than in Valencia. By the difference of time, we know the distance, in longitude, to Valencia […], and you should note that you must give to each hour of difference, 15 degrees, and to every minute of the hour, one degree.[17]

Once Faleiro had been withdrawn from Magellan's project, Magellan would choose the cosmographer Andres de San Martin (?-?) to be in charge of the operations carried out to obtain longitude. That was a crucial task to prove Magellan's ideas about Moluccas localisation. San Martin selected the procedure based in conjunctions and oppositions of the Moon to calculate longitude. Castanheda wrote that during the voyage, Magellan showed the *Regimento* to the pilots and to Andrès de San Martin to get their opinions about the applicability of Faleiro's methods (Teixeira da Mota, 1953, p. 318).

> He showed to the pilots and to the astrologer Andres de San Martin the *Regimento* that Faleiro gave him to obtain the altitude from East to West, as it has been said before. Everyone examined the *Regimento* and Magellan asked for each one's opinion, to know if they could use it during the voyage. All the pilots responded in writing that they could not use the *Regimento* and it was not possible to navigate using it. And they signed their statements. The astrologer answered similarly to all the thirty chapters of the *Regimento*, except for the fourth, which stated that it was possible to know the distance East-West from one place to another using the conjunction of the Moon with fixed stars or with the Sun.[18]

For the pilots, the *Regimento* was completely useless, but for San Martin, the fourth chapter could be useful to obtain longitude (Mota, 1975, p. 318). San Martin calculated longitudes for several places where the fleet stopped. The values that he obtained and the details from some of the observations that he made to calculate longitude were registered by Portuguese chroniclers João de Barros (ca. 1496-1570) and Fernão Lopes de Castanheda (c.1500-1559), by the pilots Francisco Albo (?-?) and António de Pigafetta (1491-1534) (Laguarda Trias, 1975, p. 155-156).

João de Barros mentioned five longitude determinations made by San Martin:

> In Rio de Janeiro, at seventeenth days of December five hundred and nineteen, he observed one conjunction from Jupiter with the Moon; and at

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[17] "Manuscrito de Sevilha" (Mota, 1953, p. 131-132).

[18] Fernão Lopes de Castanheda [História do descobrimento da Índia, livro VI, capítulo VII, tomo III] quoted by (Laguarda Triàs, 1975, p. 160-161).

> the first of February five hundred and twenty he took another position of the Moon and Venus, and at twenty-three of the same month and year, another from the Sun and the Moon; and at seventeen of April of the same year, a solar eclipse, and at twenty-three of December, after he crossed the strait, one opposition from the Sun with the Moon, and all the calculations have Seville meridian as reference.[19]

If we check Abraham Zacuto (1452-1515) Almanac, we note that on 23 February, or on the closest days, no opposition from the Sun with the Moon occurred. The closest one happened on the 3rd of the same month (Zacuto, 1986, p. 198).[20] We may be in the presence of a typo by the author, or by the person who registered the data, mistaking 3 with 23.

The same chronicler mentions another longitude calculation before the fleet reached the American coast. He does not clarify where they obtained it, but we believe that it possibly happened close to the Cape Verde islands. There is no agreement on whether the fleet stopped at that archipelago. Usually, observations were made ashore, where they could get the stability needed to use astronomical instruments. However, when they arrived at the doldrums region, they should have had enough stability to execute the observations when passing close to one of the islands of the archipelago (Laguarda Trias, 1975, p. 156).

On the American coast, the first observation was taken in Rio de Janeiro, on 17 December 1519. In a text by Antonio de Herrera y Tordesillas (1549-1626), who had access to the notes from the cosmographer, there is a detailed description of the calculations that San Martin had done. The calculations were a bit complex because for astronomical calculations the days began at noon, while civil days began at midnight:

> Staying in Rio de Janeiro on 17 December, at four hours and thirty minutes in the morning, that is to say seven hours and thirty minutes before noon, we saw the Moon over West horizon, with an altitude of 28 degrees and thirty minutes, and Jupiter above it, with an altitude of 33 degrees and 15 minutes: taking the altitude of the Moon from that of Jupiter, we found the difference of 4 degrees and 45 minutes, and considering the backward movement of the Moon, until the moment it sets in conjunction with Jupiter, it gives 9 hours and 15 minutes, in which the Moon moved the said

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[19] João de Barros [Décadas da Ásia, década III, livro V, cap. X, tomo III] quoted by (Laguarda Trias, 1975, p. 158).

[20] The Zacuto's tables were completed in 1478. In 1481, the original Hebrew text was translated into Spanish, followed by translations into Arabic and Latin. The first printed edition appeared in 1496 in Leiria, Portugal, prepared by Zacuto's disciple, Jose Vizinho.

> 4 degrees and 45 minutes. Taking these from 6 hours and 30 minutes of the night, it gives Friday, 16 of December, at 7 hours and 15 minutes afternoon. Consulting Zacuto's tables we obtain one hour and twenty minutes after noon, for Salamanca meridian, for Saturday, and for Seville meridian, at one hour and twelve minutes after noon. And by Regiomontanus almanac, they believe that it occurs the same Saturday, 17 December, in Seville meridian, at one hour and 10 minutes after noon; and considering this conjunction, which happen in this meridian, at 16 December, seven hours and fifteen minutes after noon, it gives a difference of 17 hours and 55 minutes, from this meridian to Seville [...].[21]

The longitude of Rio de Janeiro that was obtained was 268º45' West of Seville. This value is incorrect, although the calculations seemed to be correct. Andrés de San Martin justified the errors with the little accuracy of the tables he had used. It was a problem that he had already noted:

> [...] from that they concluded that there was an error in the equation of movements in the tables because it was impossible such a big value of longitude. And the pilot-cosmographer Andres de San Martin said that another time he observed a conjunction of Moon with Jupiter, and he found out an error of plus 10 hours and 33 minutes.[22]

But this justification received a sarcastic critique from João de Barros:

> Because the values weren't those he expected, he complains about Regiomontanus tables, saying that the numbers could be incorrect, being the printers the responsible for this.[23]

After passing through the Strait, San Martin kept calculating the longitude. On 16 March 1521, according to Francisco Albo, he obtained the coordinates of Suluan Island, in the Philippines. The value obtained meant that the island should be in the Portuguese hemisphere (Laguarda Trias, 1975, p. 168.

The issue was very delicate from the political and strategic point of view because it opposed the Portuguese and the Spanish crowns. They

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[21] António de Herrera [Historia General de los hechos de los castelhanos en las islas y tierra firme del Mar Oceano, tomo IV, década II, livro IV, cap. X] quoted by (Laguarda Trias, 1975, p. 159).

[22] António de Herrera, cited in (Laguarda Trias, 1975, p. 159).

[23] João de Barros [Décadas da Ásia, década III, livro V, cap. X, tomo III], quoted by (Laguarda Trias, 1975, p. 158).

were dealing with an issue that was a matter of state because the longitude value gave great arguments to the Portuguese pretensions on those lands. The processes used to obtain longitude were not accurate enough to be reliable, and it was very likely that divergences might occur among the values obtained by different persons. For example, Pigafetta presented different values, placing the islands on the Spanish side. There are some reasons to believe that San Martin had manipulated the values he obtained. Albo's testimonies showed that according to the values obtained, Portugal had sovereignty over the Moluccas. It is important to highlight the fact that Albo defended values that were not favourable to his monarch. That probably means that he was very confident in the values he presented, believing that he would be untrustworthy if he decided to change them just to agree with the wishes of his monarch (Laguarda Trias, 1975, p. 168-170).

In fact, some contemporary texts suggest a possible manipulation. João de Barros refers to a testimony of a sailor from the expedition, who said that the values were changed to put the Spice Islands in the Spanish hemisphere:

> Because they saw, by the calculations of the astrologer, and also by the route they had followed and the estimation according to the Art of Navigation, that the values obtained were more favourable to us than it was to them. For this reason, they placed the lands in the route with coordinates favourable to them, and not in accordance with Andres de San Martin calculations. And because of these, and other things were done maliciously; one of them, whose name was Bustamante, testified on his deathbed. He sailed in one of our ships, from Malacca to India, and he died when the ship stopped at Maldives because he was seriously ill. And in his will, as an afterthought, he declared that for some of the values obtained by the Castilian, in the Moluccas, he gave false values, just to be favourable to the Spanish.[24]

Laguarda Trías had a more radical opinion about the longitude of Moluccas. To him, a possible explanation for the death of Magellan was related to the fact that Magellan realised that he had failed his objective. When he obtained the longitude from Suluan Island, Magellan concluded that the Moluccas were not in the Spanish hemisphere. For this reason, he should have returned to Spain, and presented himself before the King as a man who failed his mission. To avoid this shameful situation, Magellan decided to expose himself to a reckless combat in which he died. According to Laguarda Trías, the manipulations of values occurred after Magellan's

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[24] João de Barros [Décadas da Ásia, tomo III] quoted by (Laguarda Trias, 1975, p. 158).

death. Neither he nor San Martin nor Albo falsified deliberately the values they obtained (Laguarda Trias, 1975, p. 172-173).

San Martin could not have calculated Moluccas longitude because he died in May 1521 and the fleet reached the islands only in November of the same year. After his death, the longitude values were obtained by dead reckoning from the last value he had calculated in Suluan Island (Laguarda Trias, 1975, p. 173).

The history of longitude is, in fact, something fascinating, as we have just seen in the case of the Moluccas. There was still a long way to go until the longitude problem was solved with satisfactory results in late 18th century when new mathematical tools, as well as instruments, were developed, resulting in the appearance of the chronometer with reliable accuracy and the satisfactory practical implementation of the astronomical method of lunar distances.[25]

The oldest known reference to lunar distance method is from Johann Werner (1468-1522) who had explained in 1514 how to use it to obtain longitude and deserved the attention of some Portuguese scholars at the time. Rui Faleiro's proposals proved the interest of this issue. His suggestion to obtain longitude by the conjunctions and oppositions of the Moon is based on the same principle as Werner's method and can be seen as a particular case. One fact that we must emphasise is that the suggestion of the Portuguese cosmographer was used at sea. With the tables available at that time, the results could not be more accurate.

Conclusion

As mentioned in the introduction, we wanted to present an overview of the main contributions of the Portuguese to astronomical navigation during the Age of Discoveries. At the beginning of discoveries, the Portuguese used a method developed in the Mediterranean Sea, where sailors did not use any astronomical navigation techniques. In oceanic voyages, sailors could stay for several weeks, or months, out of sight of land. They needed new methods to conduct ships safely. The Portuguese adapted techniques, instruments and calculation processes, to increase the accuracy of the positions obtained at high seas.

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[25] In the last years, and much stipulated by the 300th anniversary of the Longitude Act (1714), a number of new books on the problem of the determination of longitude at sea were written, drawing new historiographical approaches to one very fascinating issue in the history of science (Dunn & Higgitt, 2014).

In 1415, when the Portuguese expansion began, some Portuguese sailors probably knew how to conduct ships using dead reckoning, a method developed in the Mediterranean. The process met the requirements of sailors sailing in this small sea, where it was possible to reduce errors every time the pilot sailed near a known shore. By the end of the same century, Portuguese had developed a new method of navigation which enabled them to sail out of sight of land during months, knowing their position and using astronomical navigation, by measuring the positions of the heavenly bodies.

The Portuguese adapted an instrument which was already in use in the scientific circles of the Middle Ages. The astrolabe that was originally used by astronomers was adapted to navigation. The simplification made by the Portuguese allowed to determine the height of the Sun and the stars easily. In connection with this question, it will be interesting to say something about the circulation of information between pilots and cosmographers. That circulation would have to exist in some way. The pilots used, for example, tables of declination, drawn up by astronomers and cosmographers. But there is no precise data on how this connection was made. What we have indicates that it would be normal that a very big gap exists between "scholars" and practical men of the sea. The mutual criticism between pilots and Pedro Nunes was real. If this were not the case, João Lavanha (c. 1550-1624) would not have had to mention in his first navigation manual for pilots, which was printed in 1595, that he had to make a series of approximations in the different processes he wanted to teach to fit the practice of the pilots. For instance, if pilots were people with a minimum level of studies, it would not have changed the scale of the astrolabe, putting the zero vertically to avoid a subtracting operation.

To determine the exact latitude of the ship, the Portuguese pilots found the necessary key in the observation of the sun at midday or the pole star at night. Of course, there were some technical problems related to the accuracy of the sun declination tables that were necessary, for example. Still, the question of the determination of latitude was practically solved during the voyage of Vasco da Gama (1469-1524), 1497-1498.

The longitude would be very different. The problem was of another kind with a much more difficult solution. Although the ideas for the determination of longitude had been suggested at the beginning of the 16th century, the truth is that it was only in the second half of the 18th century that it was solved in practice. But, the Portuguese sailors were also attentive and concerned about that matter, and there were attempts to try the astronomical methods that had been proposed in the meantime. Faleiro's proposal is something that deserves to be highlighted. One of his process to obtain longitude was used in Magellan's voyage.

It was, in fact, the Portuguese pilots and scholars who made a significant change from the art of sailing to the navigation based on scientific bases that will allow Europeans, eager to trade with the Eastern and expand their territories, to launch themselves into the great adventure of discovering the unknown frontiers of the world. For example, when England began to rise as a sea power in the 16th century, literally nothing was known about celestial navigation in England. Hence, Spanish and Portuguese navigators had to be employed, and their navigation manuals had to be translated into English (Sonar, 2010).

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