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The Advent of Scientific Aircraft Navigation

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Abstract

Two Portuguese aerial navigators, Gago Coutinho and Sacadura Cabral, crossed for the first time, from Europe to the South Atlantic in 1922; they developed and used for the first time scientific methods of astronomic navigation when flying out of sight of land: a path corrector and a precision sextant. Both navigation devices were tested during short flights from Lisbon to Madeira Island (1921) and the encouraging results obtained, allow the navigators to apply them with quite success into an intercontinental flight. The "path corrector" was invented by Sacadura Cabral and Gago Coutinho with the intent to calculate graphically the angle between the longitudinal axis of an airplane and the direction of flight, taking into account the intensity and the direction of the winds. The regular sextant used by the navy could not be applied to aviation due to the difficulty of the definition of the sky-line at a normal flight altitude. Gago Coutinho developed a new model of sextant that could be used to measure the altitude of a star without the need of the sea horizon; this new device was called "precision sextant" and was improved with an artificial horizon line defined with the help of a water bubble. This device was later improved with an internal illumination system to allow its use during night flights and was used along the First Aerial South Atlantic Night Crossing, in 1927, performed by Portuguese airmen Sarmento Beires, Jorge Castilho, Duvalle Portugal and Manuel Gouveia. An advanced version of this instrument started to be manufactured in Germany by C. Plath under the name of "System Admiral Gago Coutinho".

Keywords

History of the Sextant, Gago Coutinho, Precision Sextant

1. Introduction

Although aviation had already captured the imagination of people throughout the world since the Wright Brothers and Santos Dumont, before 1922 (First Flight from

Europe to the South Atlantic), there were no scientific methods of astronomic navigation that could allow flying out of sight of land accurately; instead, all the existing navigational devices were from maritime application and could not be applied to aviation due to the difficulty of the sky-line definition at a normal flight altitude. First transatlantic flight occurred between United States and Europe in 1919, performed by Commander Albert C. Read; for this journey U.S. Navy decided to dispose 60 warships along the route and to use directional TSF (radio communications) in the case that the weather conditions did not allow to catch sight of the projectors. Two weeks later, John Alcock and Arthur Brown using TSF, performed a flight between Newfoundland and Ireland on a non-stop flight in 16 hours in a Vickers Vimy IV twin-engine bomber Rolls Royce Eagle Engine, each of 360 hp (**Figure 1** [1]). In spite of the Arthur Brown aerial navigation skills only few observations were made revealing that they had only a limited confidence in the results. In fact, the navy sextant in conjunction with the compass, were the existing navigation devices for more than two centuries. Although the maritime sextant could not be used in air navigation, Gago Coutinho predicted that its accuracy would be a vital instrument onboard the airplanes and would allow the continued positioning of aircraft outside the range of radio frequencies, turning possible the flights over oceans without the aid of ships. The art and science of conducting ships, requires theoretical and practical knowledge to determine the successive positions from departure till its destination. Professional sextants use a click-stop degree measure and a worm adjustment that reads to a minute, 1/60 of a degree. Most sextants also include a vernier on the worm dial that reads to 0.2 minute. Since 1 minute of error is about a nautical mile (at the equator line), the best possible accuracy of celestial navigation is ~0.1 nautical miles (185.2 m). At sea, results within several nautical miles, well within visual range, are acceptable. A highly-skilled and experienced navigator could determine position to an accuracy of ~0.25 nautical mile (~463 m) [2].

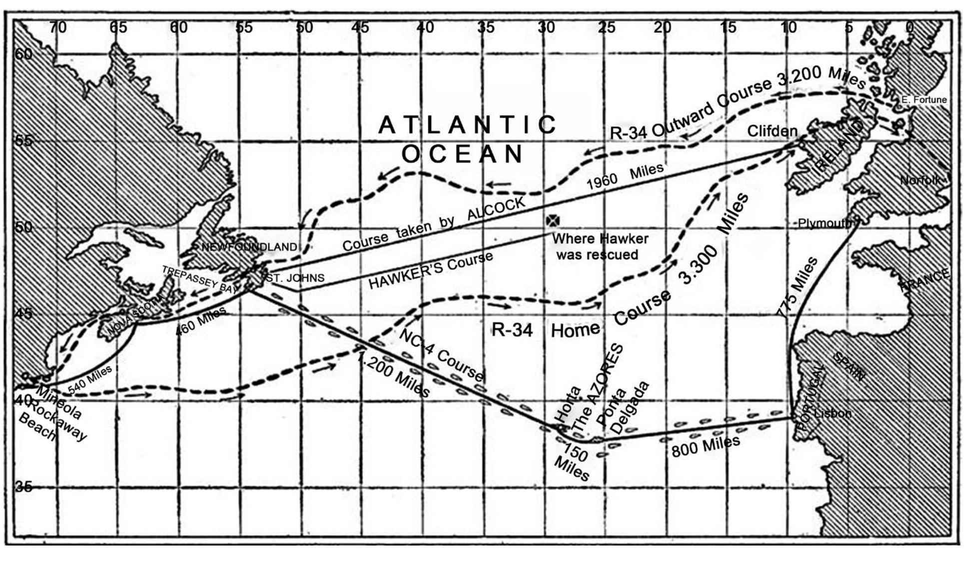

Figure 1. Map with traced trajectories performed by Commander Albert C. Read (NC-4 Course) and by John Alcock, both performed with the help of radio external means of navigation [1].

2. Scientific Aircraft Navigation Devices Developed and Tested by Portuguese

Both "path corrector" and precision sextant devices were tested during short flights between 21 July 1920 and 21 January 1921, complemented by the use of *Auss* tables, or with the collection of *Houel* tables. In 1920 *Sacadura* was appointed to serve on the *Comissão Mista de Aeronáutica*. In the same year, he and *Pedro Rosado* went to Calshot, Southampton, United Kingdom to acquire two hydroplanes F3 Felixtowe (with 4017 and 4018 numbers). These seaplanes were then prepared for the Lisbon-Funchal voyage. On 22 March 1921 with the help of the precision instruments and with Gago Coutinho, Ortins de Bettencourt and Roger Soubiran onboard, Sacadura Cabral performed an experimental flight from Lisbon to Madeira (520 nautical miles). The trajectory should be a perfect straight line and to verify the position of the aircraft three ships were used to control its position. The result was a complete success voyage with 7 h 30 m of duration and pilots started to believe that they were prepared to initiate Portuguese transatlantic flights, on the case from Lisbon, Portugal to Rio de Janeiro, Brazil, through Cape Verde and Fernando de Noronha Islands.

Over all, they sought to prove that air navigation could be just as accurately pursued as sea navigation, by deploying sextants and other available astronomical devices [2]. Figure 2 shows a photo of Sacadura Cabral and Gago Coutinho taken just before the beginning of the First Flight from Europe to the South Atlantic.

3. Scientific Aircraft Devices on the First Flight from Europe to the South Atlantic

The First Flight from Europe to the South Atlantic started at Lisbon on 30 March 1922

Figure 2. Sacadura Cabral (left) and Gago Coutinho (right) moments before the departure to the First Flight from Europe to the South Atlantic [4].

with a Fairey FIII-D single Rolls-Royce engine seaplane called "*Lusitânia*" (**Figure 3**). The flight had to be carried out in several stages as a result of flight range limitations of the seaplane; nevertheless, Gago Coutinho and Sacadura Cabral managed to perform the First Flight from Lisbon (Portugal) to Rio de Janeiro (Brazil). A first major problem happened when trying to sea land near *Penedos* (Saint Peter and Saint Paul Archipelago near the Brazilian Coast) where the ship "*República*" was positioned in order to refuel the seaplane "*Lusitânia*"; one of the floaters of the seaplane was destroyed by the crest of a wave and the seaplane tilted and sank shortly after. The Portuguese government decided to help the navigators: for this, a second seaplane named "*Portugal*" was delivered to Sacadura and Coutinho as a way to allow the pilots to complete their flight journey; in its first flight stage, nearly seven hours after take-off, the engine stopped due to fuel carburation hiccups, leading to a forced sea landing; meanwhile the floaters began to sink slowly; Coutinho and Cabral were rescued by a British freighter. On 5 of June they received a third seaplane Fairey F III-D, called "*Santa Cruz*" that was used without further problems to travel from Fernão de Noronha to Recife. Finally they flew to several cities in the Brazilian coast, and then reached Rio de Janeiro on 17 June of 1922. For the first time in the history of the aviation the crossing of the South Atlantic had been achieved and using an instrument that enabled an aeroplane's position to be determined by astronomic navigation when flying out of sight of land [2]-[16].

4. The Origins of Scientific Aircraft Navigation

Artur de Sacadura Freire Cabral was born in 23 of May 1881 in Celorico da Beira, Portugal. In late 1890s, he worked as a topographer in Mozambique. In 1910, Cabral became graduated at the Portuguese Naval Academy. He was sent to France in 1916 in order to obtain a pilot license; shortly after he earned his pilot's license. He returned to Portugal and was appointed Commander of Bom Sucesso Naval Center and latter

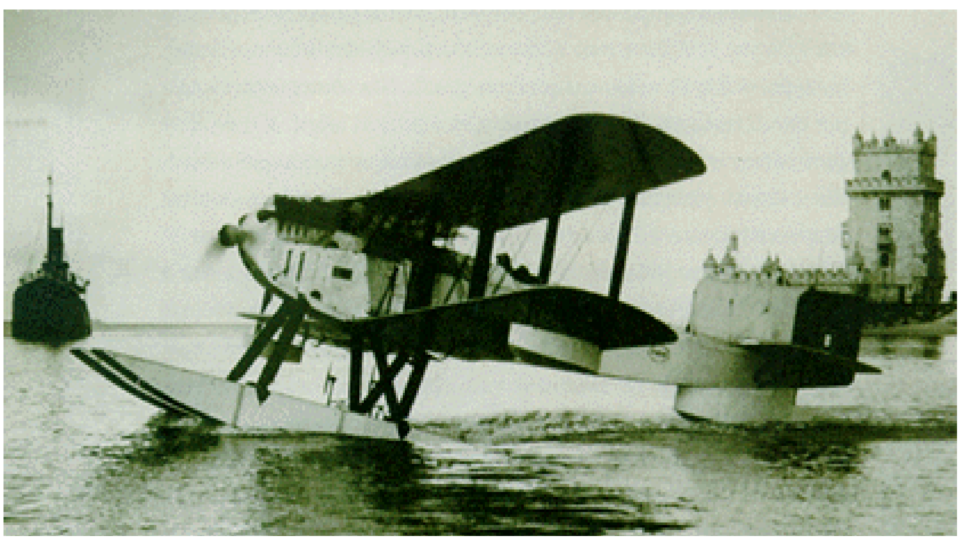

Figure 3. The "*Lusitânia*" seaplane with Gago Coutinho and Sacadura Cabral onboard, at 7:00 h of 19 March 1922—time of departure to the First Flight from Europe to the South Atlantic [2].

Director of Maritime and Aviation Services squadron commander of the Air-Naval Base of Lisbon. He was unanimously considered an excellent aviator due to his qualities of courage and intelligence. Carlos Viegas Gago Coutinho was born in 17 of February 1869 in Belem, Lisboa, Portugal; he attended the Polytechnic College at the age of 16. On 1898, he joined the Naval Academy and started to work as a geographer and cartographer. Latter, Coutinho worked as geographer and cartographer at Timor, at Mozambique, and at Angola. In Mozambique he met Sacadura Cabral. Coutinho returned to Portugal in 1918. When they met themselves at Africa, Coutinho was invited by Cabral to lead the studies related with air navigation as a form to encourage their dedication to the development of estimated air navigation in order to overcome the technical and material weaknesses that they did feel at the time. The purpose of estimated air navigation was to turn possible flying travels over the Oceans without losing themselves and as well as to reach the destination without hesitation because the scarcity of fuel did not allowed. Rather than invent a new aerial navigation device, Coutinho believed that the successful way was to usea simple resource in order to adapt the naval navigation devices, making them turn equally accurate for air navigation. The operation of air navigation should be easy and material, because air navigators did not possessed experience on wide air travels; they simply do not exist yet. And as the airplane flies at a high speed, usually over a mile per minute and fuel is limited; such operations would have to be made fairly quickly. The major conclusion that Coutinho and Cabral could draw from the experiences of previous trips was essentially to accomplish very correct route estimation, *i.e.*, to determine the needle deviation with the greatest accuracy leading this to know the mean navigation course and also at any time, to know the necessary corrections to perform due to the wind drift. While flying too high, the sea always would look like completely plan, not giving sufficient information on the strength of the wind, by simple visual observation. Because of this, Coutinho realized that the most advantageous altitude would be about 200 m. The wind drift was estimated by the help of smoke balls drawn through the seaplane to the sea surface; as they kept floating, the smoke could give to pilots a very accurate estimation of wind drift; another disadvantage of travel in greater altitudes is that the time of the smoke balls in the water and the speed of the aircraft, can disrupt the estimated navigation due to the difficulty of measure the value of the wind drift (calculated with the use of path corrector in Figure 4). A great advantage to anyone accustomed to the sea, as the Navy officials, is the fact that the simple visual observation, when in a small heights, provides a very approximate wind direction and its strength to the nearest 2 to 4 miles. It allows an approximated idea of the wind drift. Whatever the instrument for astronomical observations, the use of the artificial horizon is subjected to an error in the vertical momentum, such error not exist when we observe the horizon at sea. The instrument to be used in air navigation must be a sextant that allows observing the sea horizon as well as the artificial horizon. With regular weather, the sea horizon is good to see at about 30 m of height and generally there are no problems to descend to this altitude during the short time necessary to observe the heights of the stars. In general, the estimated navigtion was made in

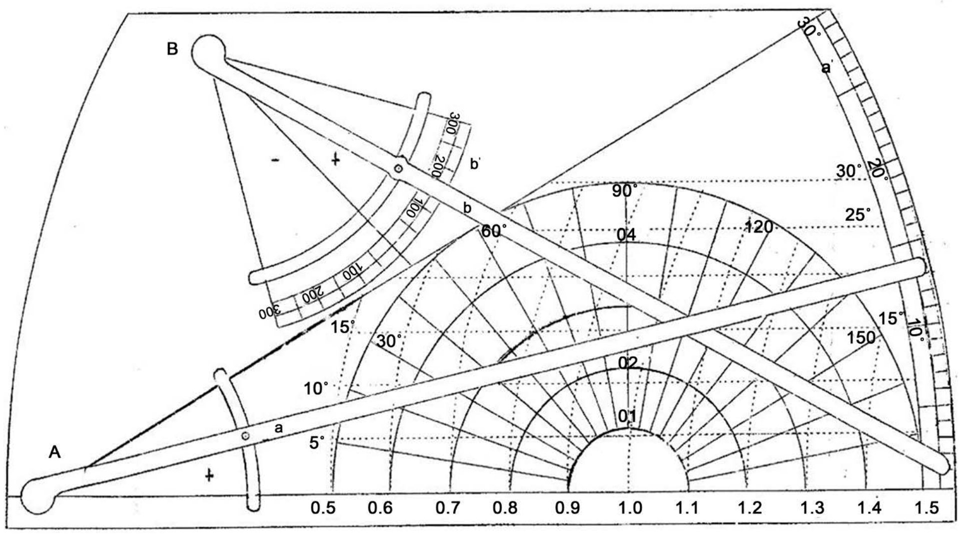

Figure 4. Original version of the path corrector presented by Sacadura Cabral at *Premier Congrés International de la Navigation Aérienne*, (First International Congress of Aerial Navigation), at Paris on November 15/25 of 1921 [11].

a similar way to that what was done on ships, and it was graphically recorded on the card by which the crew navigated [2] [8].

4.1. The "Path Corrector"

The path corrector [2] [4] [7]-[11] was based on the following basic geometric principles (**Figure 5**): Being AB = A'B the paths travelled in units of time, A and B the wind drift observed in each of the directions AB and A'B, the AC line, represents the magnitude and direction of the wind that acts on the plane while flying from point A to point B. More in detail, drawing a C'F' line, parallel to AB, and drawing a distant point C and with the centre at point A and radius AB, drawing the arc of a circle until find the C'F' line. From point C' drawing a parallel C'B' to BC, with the same length, which will represent the wind speed. Thus, if changed the path of the angle BAC' and run for one hour the path AC', the wind at this time(one hour) will run from C' to B', which can really permit to follow from A to B' following in the primitive direction AB and therefore with the useful speed equal to AB'. The C'AB' angle will be the final wind drift. Greatness is determined by the distance from point C to line AB, that is, by his *sin*, being the radius unity the value of the airplane speed. All winds represented by a line starting at point B to the direction to line CF will require the same rerouting represented by the angle C'AB; but the useful speed AB' will vary with the strength and direction of wind. Marking from the point B' an extension of the line B'B, one length B'N equal to the desired speed AB; NB = AB' and BC = B'C'; the triangle NBC = AB'C'; the flank AC' = CN; therefore, NB' = NC. The NC arc of circle with centre at N, the points will pass in B' and C' [2].

Same reasoning can be done if the wind is represented by line BD, starting from point B to the arc of circle B'DC; in this case the parallel B'D' = BD would cut straight

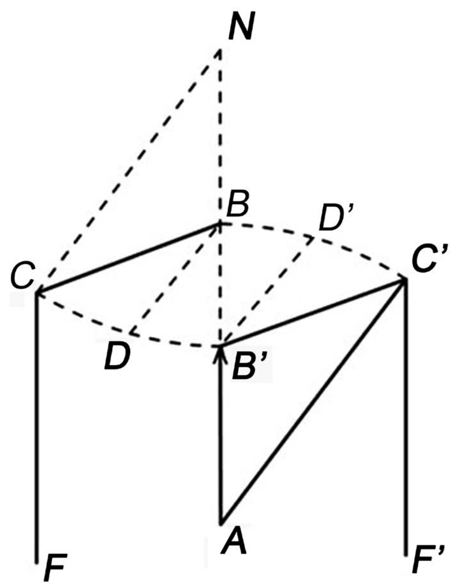

Figure 5. Detailed cases of the geometric principles of the path corrector [2].

the arc of circle BC' at the point D' that will be at the same distance D to the line AB. Thus, if the wind is BD, and the useful speed of the aircraft would be AB', and as the first case studied, with the wind BC, or with any wind or represented by a line starts at point B and ending at the circle arc BC. This arc is the geometric place of the ended lines, which represents all the winds, which starting at point B, and combined with the speed of the plane (AB), allow the use of the same final speed AB', in the desirable direction to fly, AB'. Dividing the length AB in 10 equal parts and in each of these points of division draw arcs of circles with radius AB, and with their centres in the extension of BN, from AB, it could be concluded that by simple inspection, which is the useful speed in tenths of a fraction of the own speed of the aircraft, for each of the winds which, in direction and speed we can imagine. Similarly as already deduced, the parallel lines to AB, that have distance equal to the sine of its angles, ranging for example from 5 by 5 degrees, will give the wind drift to correct, in a way to make the plane fly really this direction, with the lateral action of wind. The path corrector provides observations of wind drift in two directions, one being what will be pretended to navigate, and the other, a path 45 degrees related to the dominant wind on top. Two pointers moving around two points, which represent the points A and A' of Figure 6, marking their graduation to the wind drift observed, with the respective sign: angles measured by the right side of the airplane, are marked with *plus* sign, because it indicates the need for course correction, adding the wind drift to get the path that should be navigated. For similar consideration, the wind drift measured by the left side of the aircraft, are marked with minus signal. For simplification of the instruments, only will be considered wind drifts with the plus signal in the first direct observation of the course, and the positive or negative wind drifts in the 2nd direction that supply positive final corrections [2].

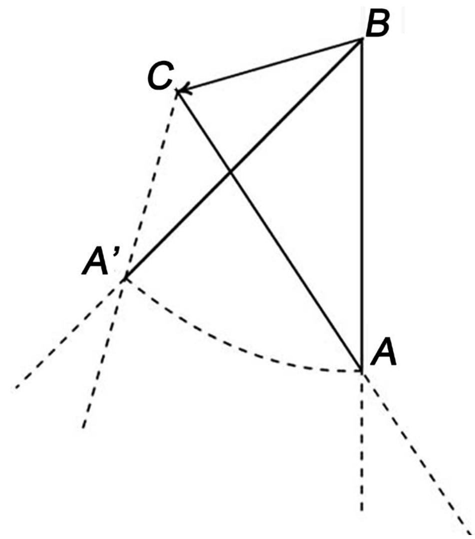

Figure 6. Geometric principles of the path corrector [2].

Generally, it could be used the plus signal of the second pointer when both wind drifts are observed by the same side of the airplane, and the minus signal in the same pointer when the wind drifts are read by different sides of the airplane. A course correction may be made without consideration of the signal, because the wind drift is made by yawing from which side the wind blows. As was used in aviation and in some marine vessels at that time, the directions were counted from 0 to 360 degrees, from North to East, South and West, in a clockwise direction. In celestial navigation, it was used a medium stopwatch, marking the Greenwich Time, and an average medium counter. In the prediction of astronomical observations during the night, a stopwatch was used to adjust the sidereal time of Greenwich [2]. The Deutsche Lufthansa created an air navigation course in the Naval School of Lubeck, where they thought the Coutinho's sextant and its new path corrector. Nissen [4] managed to expand the path corrector on air navigation above land, the *Coutinho-Fr. Nissen* path corrector (**Figure 7**). In the IV Congress of the International Air Navigation, Rome, 1927, Coutinho and Castilho, the Portuguese delegates presented and defended the Portuguese methods. In 1932 also in Rome, in the I International Congress of Transoceanic Aviators highest honors were given at the Portuguese crossings of the South Atlantic and their methods of navigation. It was used by many of the major airlines of the world throughout the 1930's [10].

4.2. The Precision Sextant

Figure 8 illustrates a precision sextant of Gago Coutinho (1922). The calculation of the position by the observation of celestial bodies requires knowledge about the altitude of the airplane, which may be concluded from the observation of the aneroid or by the apparent shadow of the wings of the airplane on the sea, whose size was known. The navigators were carrying special tables, to help measure the altitude of the airplane. Represented in these tables was the height of the Sun. The tables provide a coefficient to

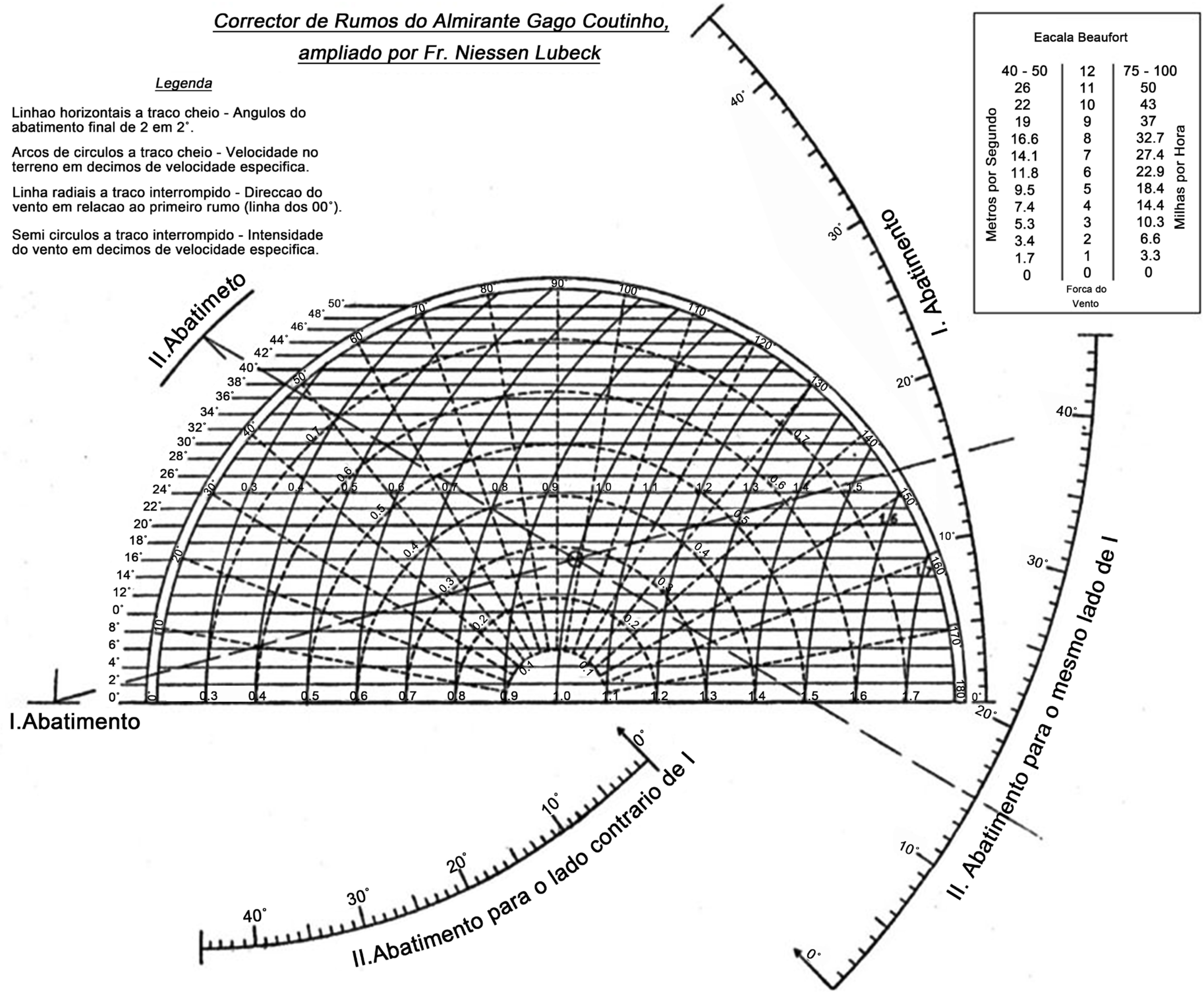

Figure 7. Coutinho-Fr. Nissen path corrector [4].

multiply by the cotangent angle of the shadow, measured from the sextant, never using the altitude of horizon clouds. From the observation of the height and time, it could be concluded the line of height, by the resolution of the spherical triangle of position. The formula, with which the navigators were more familiarized, was in essence the general formula:

$$\sin A = L\cos D\cos P - \sin L\sin D \tag{1}$$

where: $A \Rightarrow$ Height; $L \Rightarrow$ Latitude; $D \Rightarrow$ Declination, and $P \Rightarrow$ Polar distance of the star.

Working the equation other parameters could be found:

$$\cos L\cos D = C \tag{2}$$

$$\sin L\sin D = S \tag{3}$$

$$\operatorname{cotg} L\operatorname{cotg} D = T \tag{4}$$

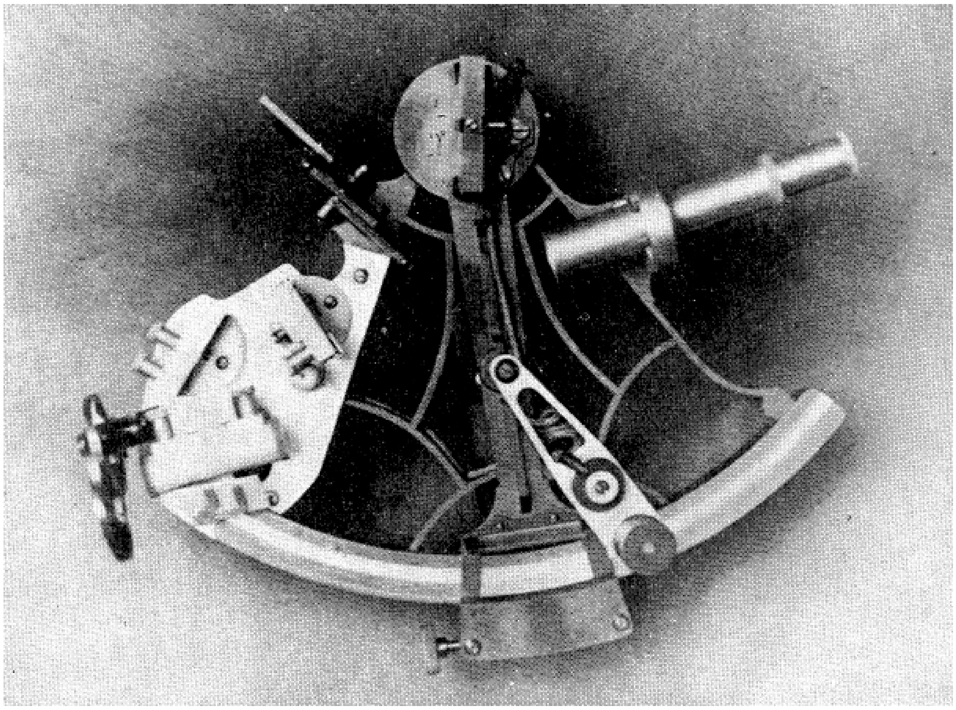

Figure 8. Precision sextant improved and used by Gago Coutinho along the First Flight from Europe to the South Atlantic in 1922 [4].

And defining equations in order to *sin A*:

$$\sin A = C\cos P - S \quad (5)$$

$$\sin A = S\left(\frac{C}{S}\cos P - 1\right) \quad (6)$$

$$\sin A = ST\left(\cos P - 1\right) \quad (7)$$

$$\sin A = S\left(\frac{T}{\sec P} - 1\right) \quad (8)$$

For the calculation of azimuth, it was used:

$$\operatorname{cosec} Z = \sec D \operatorname{cosec} P \cos A \quad (9)$$

In order to avoid disadvantages of the use of maps with different scales, the navigation was planned and carried out by a special map, designed specifically in cardboard, on which used the secant conical projection and a constant scale of 1/2 mm per mile. The line of navigation to follow was designed in red and the lines of time were marked with a protractor graduated in mm (2 miles). On the eve of each trip it was calculated values of S and T for each of the estimated points. Then a table were made and preached in front of the observer. In this table was also the secant value of D, to calculate the azimuth. With S and T values tabled, and with the search of logarithm of secant P, and with the use of the *Auss* tables, or the collection of *Houel* tables, it could be solved quickly the calculation of the estimated height and the calculation of the azimuth to the reference point, which was chosen in the navigation card [2]. After the First

Flight from Europe to the South Atlantic, Gago Coutinho worked almost daily in perfecting his sextant and began to share with Jorge Castilho all the improvements that might be introduced in that device. This subject would be of Castilho's particular interest since a long Portuguese Aerial Journey was being prepared by Sarmento Beires whereas Castilho should be invited as a navigator and would use the Sextant "System Admiral Gago Coutinho". Beires had already tried an Aerial Circumnavigation flight attempt in 1924, which became known as the First Aerial Journey from Portugal to Macau [12]. The improvements on the sextant were namely: build a left handed sextant, freeing thus the right hand for immediate annotation of heights and time, eliminating all memory resources; a special lunette inclusion for stargazing, making the device suitable for more stringent observations and maintaining its scientific certainty during all 24 hours of the day; the detection of a star (or a planet) and its respective adjustment became made simultaneously with a single screw, by the inclusion of a screw adjustment step (**Figure 9**). In 1926 Jorge Castilho performed several flights in order to rehearse and practice the methods and devices of celestial navigation. For that purpose on 8 March 1926 Sarmento Beires, Pais Ramos, Jorge Castilho and Manuel Gouveia, taken off in two aircrafts Napier Vickers and flew Amadora-Morocco-Amadora. In addition to testing the sextant, the four hundred kilometers to each side of this trip most of the time without land sighting revealed that Jorge Castilho possessed the required competence for long range flights [13] [14]. During the night from 16 to 17 March 1927 a Portuguese crew flew 2,595 km over the Atlantic Ocean from Guinea, Africa to Fernando de

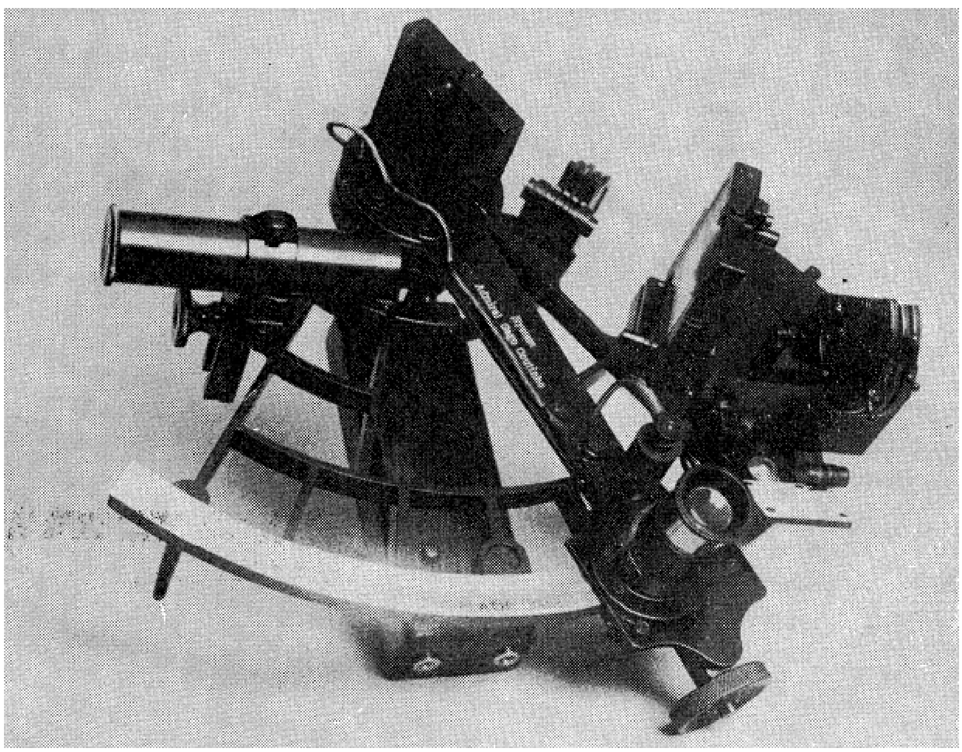

Figure 9. Precision sextant improved by Gago Coutinho and Jorge Castilho and used by Jorge Castilho along the first aerial South Atlantic Night Crossing [4].

Noronha Island, Brazil. The flight was made only by astronomical processes navigation resources that proved again to be absolutely feasible and trustworthy, regardless day or night lighting conditions. Jorge Castilhowrotein his report: "… *Creio que foi a primeira vez que um avião passou uma noite inteira a voar sobre o mar e sem ter para se orientar outro recurso além dos processos astronómicos que se mostrou serem absolutamente praticáveis e dignos de confiança*…"; "[…I believe it was the first time that an airplane flew an entire night over the ocean having for its guidance resources only astronomical processes which proved to be absolutely feasible and trustworthy…]" [13] [14].

5. Foreign Credits to the Scientific Aircraft Navigation Portuguese Devices

References to instruments and methods created in Portugal were published in almost all aeronautical magazines: *Nautical Magazine* (1923); *United States Naval Proceedings*; *Navigatione Aerea*, from Italy; *Icaro* and *Boletin Oficial de Aero Club de España*; *Conquete de l'air*, from Belgium; *L'air*; French revue; *Navigacion Aerea*, from J. Aymat, Barcelona, 1928 and *Avigation*, from Bradley Jones, London, 1931. In 1929 Captain Witten man navigated the Graf Zeppelin around the world using a Coutinho's sextant. With this spectacular record, the design was the hit of the 1930 Berlin Air Show. Until 1930, several countries had acquired this instrument: Portugal, Germany, Japan, France, Spain, U.S.A., Chile, Italy, Netherlands, Sweden, Argentina and Bolivia. The Portuguese Navy, who had rights to the development, contracted with the prestigious German firm of C. Plath for production. Coutinho regularly gave to them details for the improvement of the sextant until 1938. After the II World War, sextants evolved to become practical. The air transport aircraft came to be equipped with domes of transparent plastic, requiring no corrections to the readings, such as predicted by Coutinho. In February of 1969, by the Coutinho's centenary birth, Frank Borman was in Portugal. The Commander of the Apollo-8, the first that orbited the Moon from 21st to 27th December 1968, gave a lecture at the Portuguese *National Laboratory of Civil Engineering*. He explained that the principle of Gago Coutinho was present in the Apollo-8 flight. In fact, "a sextant used in aeronautics for the first time in the world by the Portuguese genius" was mounted to a telescope. He detailed that these instruments was connected to a computer, which indicated that the final accuracy of the error was 0.001 degree. In 1971, Francis Millet Rogers, from Harvard University write a book entitled "*Precision Astrolabe; Portuguese Navigator and Transoceanic Aviation*" published in Lisbon by the *Academia Internacional da Cultura Portuguesa*, and distributed in the U.S.A. by W. S. Sullwold, Tauton, Mass. In 1973, Colter, H. C. publishes his work entitled "*An Early Portuguese Contribution to Air Navigation*", in the *Journal of Navigation,* (Volume 26, Issue 03, July 1973, pp. 382-385). In this paper, the author made references to Coutinho's process of navigation "which made the calculations on the eve of the flight so that the line position was drawn in the flight chart nearly 5 minutes after the end of observation, and while crossing the Atlantic South, close to equator line, this time was reduced to 3 minutes" was an unprecedented simplification studied by Coutinho [2].

6. Conclusion

Two Portuguese aerial navigators, Gago Coutinho and Sacadura Cabral, crossed for the first time, from Europe to the South Atlantic in 1922; they developed and used for the first time scientific methods of astronomic navigation when flying out of sight of land: a path corrector and a precision sextant. Both navigation devices were tested during short flights from Lisbon to Madeira Island (1921) and the encouraging results obtained, allow the navigators to apply them with quite success into an intercontinental flight. The "path corrector" was invented by Sacadura Cabral and Gago Coutinho with the intent to calculate graphically the angle between the longitudinal axis of an airplane and the direction of flight, taking into account the intensity and the direction of the winds. The regular sextant used by the navy could not be applied to aviation due to the difficulty of the definition of the sky-line at a normal flight altitude. Gago Coutinho developed a new model of sextant that could be used to measure the altitude of a star without the need of the sea horizon; this new device was called "precision sextant" and was improved with an artificial horizon line defined with the help of a water bubble. This device was later improved with an internal illumination system to allow its use during night flights and was used along the First Aerial South Atlantic Night Crossing, in 1927, performed by Portuguese airmen Sarmento Beires, Jorge Castilho, Duvalle Portugal and Manuel Gouveia. An advanced version of this instrument started to be manufactured in Germany by C. Plath under the name of "System Admiral Gago Coutinho". The original problem proposed to encourage the dedication to the development of estimated air navigation in order to overcome the technical and material weaknesses at that time, was solved. It was proved to be easier for other navigators with less experience, make great travels crossing the sea, using only the astronomical observations, at least in regions without cloudy sky. It will be sufficient to use processes and tools similar to those used and described, which could be improved and which are adapted to the sea navigation. And without cloudy sky, from 1927 onwards, pilots could manage to fly along 24 hours a day regarding every light condition.

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