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ASTRONOMICAL NAVIGATION AT THE BEGINNING OF THE THIRD MILLENIUM

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Abstract. The astronomical navigation[1], as a discipline of applied astronomy, which deals with solving navigational problems by observing celestial bodies, mostly by determining the position of the ship, for many centuries was dominant in orientation of seamen and directing the ship on the open sea. It achieved its full and almost complete development in the second half of the XIX century. Since then its development is a result of technological advancement of instruments and equipment, without essential advance in accuracy and use. In the second half of the XX century its use was marginalized, and at the start of the third millennium almost pushed aside by electronic navigational systems, mostly satellite system GPS.

1. INTRODUCTION

It is not an isolated occurrence, but a rule, that the scientific and technological advance makes redundant the use of means and methods of entire disciplines of science and practice of the human civilization. What is the position of astronomical navigation in that chain of origin, development and disappearance, and why is it such?

The navigation, as a science and skill of directing the movements of a ship on the best possible route from one point on Earth to the other, was developed because of the need of sailing, because of the need to transport goods and people over sea. Underlining the transport is the money, or trade with goods and services (even in times of great geographic discoveries) using optimal, meaning the shortest and safest, sea route between distant ports. The actual sailing in essence comes down to knowledge of parameters of the sailing (which course and speed) and control of that sailing, or determining at any given time what is ship's position (determining the position). Relating to the area of sailing, the navigation is divided into offshore and oceanic, which differ significantly. As long as the sea shore was visible, directing the ship using means and methods of terrestrial navigation was easier, more dependable and filled the crew with the sense of confidence. However, only after less than a day of sailing, even with low speeds of, for example, 6 knots, the sea shore of even up to 1,000 meters height would disappear from the horizon, and seamen can only see the constant line of the horizon of the open sea. This fact explains the reason for creating astronomical navigation, as a discipline of the applied astronomy, or discipline of navigation, which

[1]The expression *celestial navigation* can be also found in the literature.

solves navigational problems, first and foremost by determining the position of the ship by observing celestial bodies.

2. DEVELOPMENT OF ASTRONOMICAL NAVIGATION

The only possible means of orientation on the open sea until middle of the XII century, when the Arabs brought the Chinese compass to the Mediterranean area, was using the celestial bodies[2]. Only with the appearance of these compasses, called calamites, the direction and the azimuth could be determined using the device, and not by guessing. Contrary to orientation using the celestial bodies, which hasn't changed to this very day, determining the course and azimuth[3] became more and more dependable and correct with the development of the compass. With the discovery of variation and deviation, and after that compensation[4] in XIX century, magnetic compass reached its full development and present-day form. This type of compass, still mandatory according to SOLAS[5] convention, has today been almost completely replaced by gyro-compasses[6].

The first essential determining of position, more precisely in one of its coordinates (latitude) begun in the XIII century, by measuring the altitude of celestial bodies in or around the meridian. Measurements were conducted using cross-stick, quadrant and astrolabe.

Inability to determine longitude has forced the sailing along the latitude parallel, or sailing along the meridian to the parallel of the destination harbour, and then by sailing along the same parallel, towards east or west, to the destination harbour. Although Johanes Werner has proposed as early as 1514 that position of the Moon in relation to brighter stars be used to determine the longitude, known as the method of Moon's distance, due to insufficiently correct coordinates of the Moon and insufficiently precise instruments, longitude could not be determined with precision better than 0.5°.

Independently from one another, Thomas Godfray and John Hadley have, in 1730, constructed the quadrant, or the octant, as modern navigation instruments, by using the Newton's discovery in 1699 of the principle of coinciding of double reflected image of the celestial body with the direct line of horizon. With the usage of discovery of nonius made by Pierr Vernier (in 1631), Hadley in 1757 constructed the sextant, which allowed the measuring of angles in navigation with precision of 0.1', which is the terminal precision until today.

The problem of determining the longitude on sea was in essence reduced to the problem of measuring the time, or determining the time scale of one (prime) meridian. That problem was highlighted after the sea catastrophe of 1707, in which 2,000

[2] First written findings about the use of celestial bodies in orientation on the sea can be found in Homer's "Odyssey", dating from XV century B.C.

[3] The first use of calamites in measuring the bearing, or precursor of the bearing circle is found recorded in the year 1248 in the book "Epistola de Magnete" from 1269.

[4] Discovery of variation (magnetic declination) is attributed to the Chinese (XI century) and Columbus (XV century). Deviation was discovered in the year 1627, and the first procedures of compensation of magnetic compass were used by Matthew Flinders (in 1801 - 1802). George Airy and W. Thompson, better known as Lord Kelvin, have contributed to the present-day form and development of magnetic compass in XIX century.

[5] Convention on protection of human lives at sea, SOLAS (Safety of Life at Sea)

[6] The first gyro-compass was built by Anschütz and Kempfe in 1907.

seamen and soldiers have perished, so that The Board of Longitude has been formed in England in 1714. The Board had the authority to award anyone 10,000 pounds[7], who came up with the solution for determining the longitude on the sea with the precision within $\pm 1^\circ$.

Only the fourth chronometer[8] made by John Harrison in 1736 has satisfied the conditions of the Board, and the introduction of the ship chronometer created the conditions for solving the navigational triangle and determining of observed celestial position. More precisely, ship instruments have reached the stage of development which allowed precise enough and reliable position to be determined.

Only the methods were missing. American captain Thomas Sumner has discovered the celestial line of position[9] on 17 December, 1837, while sailing from Charlston to Greenock, in the area of Smol lighthouse. Understandably, to uniquely determine the position (which is defined by two coordinates) two lines of position are needed, or measuring the altitude of two celestial bodies[10], which creates condition to solve two unknown values in the navigational triangle.

With already known longitude (Johson's) and latitude (Borde's) method, there was also the altitude method[11], which was discovered in 1875 by Marq d'Saint Hilaire, which almost concluded[12] the development of methods.

3. BASIC CHARACTERISTICS OF ASTRONOMICAL POSITION

Basic characteristics of applied astronomical navigation are:

- Usable in all areas of sailing around the Earth,
- Application is autonomous and passive, because when having the instruments and equipment (nautical almanacs and publications) it does not depend on the others (persons and states), and it does not emit any energy off the ship, and thus does not give out the presence of the ship, nor makes its detection possible,
- The usage is conditioned by optical visibility (of horizon[13] and celestial bodies), or the state of cloudiness,

[7]For solving the problem with precision within the $40'$ the award set was 15,000, and within $30'$, for that time enormous sum of 20,000 pounds.

[8]Even though Henlein already in 1500 has constructed a pocket watch, the instability of its daily rate did not satisfy its use on ship. Variation of daily rate of mechanical ship chronometers is within the limits of 0.2 to 0.3 seconds.

[9]Line of position is in general, the position of points on which the observer is positioned. Line of position in the astronomical navigation is a circle on the Earth from which the observed celestial body has the same altitude. Near the position it is approximated with the direction which is the tangent (normal to the azimuth), or a chord through two relatively close points of circles of equal altitudes.

[10]Observing one celestial body is being used over the time period long enough, to reach the change due to apparent daily movement of more than 30^0. In theory, it is possible to determine the position by just observing one celestial body, but it has no value for the practice. Measuring the azimuth in ship conditions is not possible with satisfactory precision (better than $0{,}5^0$) which is insufficient for requested precision of position when solving the navigational triangle.

[11]This is the simplest and quickest method, is dominant in usage to this very day.

[12]In XX century, methods of directly calculated coordinates of the fix have been developed, which were not widely used until the widespread use of computers.

[13]In the moonless night (and with small altitudes of the Moon) the sea horizon is visible from the moment of the beginning of astronomical twilight (the altitude of the Sun 18° below the horizon) to the ending of astronomical twilight. This does not apply to the measurements of altitudes using the sextant with artificial horizon.

- Even though the precision of measurement using the sextant is 0.1′, the precision of measuring the altitude[14] and precision of determining the position is by more than one order of magnitude worse and is between 1.5′ and 3.0′ (or a mile[15]) with well trained seamen,

- The time of determining the position (measuring and calculation) with two celestial bodies takes a couple of minutes (using the most modern equipment) and up to 30 minutes (using classical equipment).

The indicated characteristics fulfilled all the requirements of navigation on the open sea and enabled the development of oceanic transport, and even the military use, ever since the middle of the previous century. There was no important advance in astronomical navigation from the latter half of XIX century, from the time of sail ships and Marq d'Saint Hilaire, until now. There was some development, but as a consequence of technological advancement in other areas.

Sextants with artificial horizon[16] have been developed (air bubble, periscope and gyroscope) which in essence use the same principle, but make possible the observation even when the sea horizon is not visible. This enables the observation to be carried out during the entire night, but the precision of measuring has not improved, even the opposite, it is lower than when using the classical sextant. Even the construction of the radio-sextant (after WWII) has enabled the measurement of altitudes to be made (only of the Sun and Moon) independently of visibility conditions, but with decreased precision, and with more complicated and expensive equipment.

Also, the ship chronometers were developed, as a result of development of clocks and the Time service in general. The problem of maintenance of time on the ship has been greatly minimized in the XX century with the emitting of the signal of the exact time. Demands for the exact time in astronomical navigation do not exceed the precision better than one second, which can be achieved today easily without much trouble or effort.

The procedure of calculation of the line of position has been significantly shortened. First through the appearance of numerous tables of different kinds, for solving the astronomical triangle, or calculation of elements of the line of position (altitude and azimuth), or geographical coordinates of position. The procedure of calculation was further shortened with the usage of numerous types of pocket calculators and personal computers, but the shortening of time needed for determining the astronomical position is after all limited by the duration of measuring the altitude (preparation, measuring, reading) and can hardly be reduced to less than five minutes, even in the modern practice.

[14]The precision of the altitude measurement is dependent mostly on the observer, visibility conditions of the horizon and state of the sea (rocking of the ship), and less on the quality of rectification, or the error of the sextant.

[15]The error of measuring the altitude is directly and completely incorporated into the error of the line of position, thus for example, the error of 1′ in altitude is causing the error in the line of position of 1 mile (a mile is 1852 m and it corresponds to the arc of the great circle on the Earth of 1′).

[16]Already in 1733 Halley added to the quadrant a vessel with the alcohol, creating the first artificial horizon on any instrument, but this article refers to the more modern instruments.

4. THE FUTURE OF ASTRONOMICAL NAVIGATION

The faults in mentioned characteristics and inability of their significant improvement and the development of science, equipment and technology in the XX century caused the expansion of electronic navigational systems. Usage of radio-goniometry to determine the ship's position can be taken as the starting point of development of electronic navigation. The first radio-beacon was erected in 1921, and during WWII electronic hyperbolic systems Consol, Loran-A and Decca have been developed. The precision of position, determined by these systems, was slightly better or comparable with the precision of astronomical position, but the position could be determined at greater distances from the shore[17]. Even the later-developed and better quality system Loran-C has not significantly enlarged the area of world sea on which the position of the ship could be determined, and on considerable part of it position from a astronomical observation had to be determined.

Only the electronic hyperbolic system Omega[18], as a global system, has enabled the position to be determined on almost entire surface of the Earth, at any moment. The precision of determining is close to that of position from a astronomical observation, with the time of determining significantly shortened (to just 10 seconds), and is independent of the visibility conditions or time of day or night.

After the first attempts of using the Earth artificial satellites for navigational purposes, the satellite system Transit[19] was developed in 1964 for military needs of the USA, which was commercialized in 1967. Although the precision using this system is by the order of magnitude better then when using the position from a astronomical observation, and the process of determining it has been automated, the possibility of determining the position was at intervals between 15 minutes to 2 hours. As the time of 2 hours, without observed position on the open sea, is not of great significance, the appearance of satellite system marked definite decline of importance and usage of astronomical navigation. The marginalization of astronomical navigation has gone further with the development of satellite system GPS/NAVSTAR[20].

This global satellite system[21], today and in the near future is a dominant one, having the following characteristics:

- enables the three dimensional position on any point on and above the Earth to be determined, at any moment,
- determining of the position is continuous (every second) and automated,
- determining of position is independent of weather conditions (visibility and cloudiness),
- precision of position in real time is between a few meters (for users of P code

[17] The range of surface waves of transmitting stations is up to 700 miles, and spatial waves 600 – 1,000 miles (daylight), or 1,400 – 1,600 miles (nighttime).

[18] Attempt of development of electronic system of great range, on very low frequencies of 10.2 KHz, made in 1940 has failed and was abandoned. Only in 1957, the system Omega was developed, on the same principle, using the same basic frequency.

[19] NNSS (Navy Navigation Satellite System), better known under the name Transit, was developed from attempts of developing the Pathfinder system, and the first satellite Transit-1B was launched on 13. 04. 1960.

[20] GPS (Global Positioning System) came about gradually, immediately after commercialization of Transit system, and is in full configuration for ten years already.

[21] Satellite system of similar capabilities, under the name GLONASS, was developed by the former Soviet Union, while the European Union is also developing the Galileo system.

and two carrying frequencies) and 100 m (for users of C/A code only and modest commercial receivers), which is by two to three orders of magnitude better than the precision of position from a astronomical observation,

- handling the receiver is simple even without any greater expert knowledge of the seamen (even the non-professionals), as opposed to the knowledge needed in astronomical navigation,

- the receiver is relatively cheap, comparable to equipment for astronomical navigation, and

- it allows incorporation into integrated and automated systems of control and steering the ship.

The superior quality of satellite navigation systems compared to characteristics of astronomical navigation is undeniable, so it is completely understandable that the usage of the latter is disappearing. The appearance of global navigation systems produced the terminal marginalization of the astronomical navigation. The possibility is created of determining the position of the ship on the open sea (ocean) more often than when using the astronomical navigation. With that, the precision of position was not even the determining factor, because the International Maritime Organization is defining as a standard of precision of position, in areas outside of approach to the harbor, the value of 4% of distance to the closest hazard, with maximum value of 4 miles, which would suit the area of open sea[22]. The decisive factor was not even the duration of determining the position, or the time passed between two consecutive determinations of position, because on the open sea the precision of summed position satisfies the requirements during several hours of sailing[23]. The problem appears when there is cloudiness (especially when it lasts a few days), so the dependence of the astronomical navigation on weather conditions involves its significant limitation. This dependence can no longer be tolerated by today's sea traffic and its safety.

The usage of astronomical navigation does not mean just determining the position of the ship, but also solving the series of other tasks, but they equally have been marginalized. Just as an illustration let us mention some of them. According to the regulations for preventing collition at sea, position light have to be turned on (shining) from the moment of sunset to the moment of sunrise, and deck lights have to be turned on from the moment of civil twilight until the civil morning twilight. It is clear that these times need to be calculated for the position of the ship (which is constantly changing), which is not a problem for a professional and a seaman versed in astronomical navigation. However, today the most common practice is to leave the position lights turned on at all times, so the need for such calculations has been reduced in practice.

Until the appearance of radar[24], visual observation was irreplaceable way of discovering objects on the sea, especially of enemy war ships. Until the middle of the

[22]In practice of sea traffic of developed countries the permissible (95%) error of position is up to 4 miles on the open sea, 1 mile in shore sea, 0.25 miles in territorial sea, and 20 meters in inner waters.

[23]Empirical correctness of dead reckoning position is around 5% of distance traveled (with fine weather), and up to 10% (with bad weather), so that even with the high speeds of 30 knots, the error of dead reckoning position would be less than 4 miles during 12 hours of sailing in all weather conditions.

[24]The first radar was constructed by Robert Page with his associates in 1935, and the USA has already tested the first radar on the war ship in 1937, and after WWII it was commercialized, and is mandatory on every ship today.

XX century, calculations of time of rising and setting of the Moon, or the moment when it reaches the altitude of 30 $^{\circ}$ or more, served for discovering enemy ships, or covert approach to regions under action of friendly ships. In fighting actions of today, the visibility conditions are irrelevant, because the means of detection and guiding the weapons systems are no longer based on optical visibility, so the mentioned calculations are no longer needed for this purpose.

Still the control of deviation of compass (magnetic, and even the gyro-compass) on the open sea can not be performed using other methods but only by observing the celestial bodies. However, this task that can be performed by educated and true professionals, is disregarded in practice, and the dependability of sailing is secured by installing several magnetic and gyro-compasses (which are generally always turned on, and their controls are performed in shore area, being mandatory after the repairs).

5. CONCLUSION

It is not disputable that the significance of astronomical navigation, after its having been used for many centuries and its great contribution to the development of modern civilization, has meanwhile dwindled. The first question is whether it is necessary to study the astronomical navigation during training of the seamen? The answer to this dilemma has not been clearly stated yet, so there are already countries in which this subject is left out of the curriculum, but it is still being taught in most of the countries.

Supporters and advocates of rational and pragmatic approach to this matter hold that learning of this subject is unnecessary, because it is not used in the practice of sailing and after only a short period of time both the knowledge and the skill pale. In a time of intensive sea traffic priority must be acorded to a rational and appropriate spending of resources, to faster turning of capital and profit as originators and directory of the development, to the training of seamen in the shortest time and the cheapest way, who will confidently and without any risk guide the ships loaded with people and goods.

Supporters and advocates of tradition maintain that seamen have furtherhin to learn this subject. The astronomical navigation is one of the basic subjects for the profession, which qualifies the seaman, whose professional culture must be much broader than the tasks in guiding the ship. The knowledge, skills and habits gained by learning it are influencing other subjects and the practice of a genuine professional.

The astronomical navigation has reached its peak in the golden times of sail ships and together with them, with the strong backwind, is quite surely sailing into the history. If it is said that the possibility of using the technologically modern navigational systems might be limited because of its military (war) use and possible destruction, hence be forced to apply the astronomical navigation, the civilization will have much more serious and existential problems than gaining the skills and teaching the seamen again to direct the movements of a ships relying on the observation of celestial bodies.

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