THE ROLE OF CELESTIAL NAVIGATION IN MODERN DAY AND FUTURE NAVIGATION

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Abstract

This paper discusses the current and future role of celestial navigation and its application on board ships and in maritime educational institutions. Accordingly, the question is whether the governing bodies of the maritime industry should maintain their position unchanged or whether they should increase or decrease the importance of celestial navigation as part of the competencies of future officers. Celestial navigation, its evolution and the various methods of application, the possibilities of implementing future technologies, have all been the subject of many papers, but still no clear answer in which direction to go and what we can expect in years to come. The paper will systematically review and analyze existing legislation and recommendations, especially STCW (Standards of Training Certification and Watchkeeping and IMO (International Maritime Organization) acts. Also, the paper will provide an overview of various papers on this topic and the existing most used methods. An overview of what is considered a modern solution is also provided. The focus is on the advantages and disadvantages of celestial navigation in the context of the future environment in the maritime industry.

1 INTRODUCTION

Since it first came into use, celestial navigation has been a key part of navigational practice. Celestial navigation remains a logical continuation of the progress of navigation techniques and the development of positioning devices, with an emphasis on classical devices such as sextants and chronometers. Throughout history, it allowed mariners to embark on voyages further from the coast.

The topic addressed in this paper examines the evaluation of the need for continuing celestial navigation education for navigators whose future will be more demanding in terms of technological-navigational innovation. For now, the IMO still recognizes the importance of astronomical navigation as a required skill that mariners still have to use [IMO Model Course 7.01&7.03, 2014]. Further to that, the IMO through its conventions, specifically through the STCW convention, continues to prescribe the education of future deck officers and includes in their syllabus requirements for knowledge and skills related to celestial navigation, for international recognition of the certificate in the manner prescribed by the STCW [STCW, 2017]. Mandatory contents of syllabuses in the context of STCW are in part related to knowledge and skills required for running celestial navigation. And it is accordingly taught in maritime education institutions, and all internationally recognized courses or other forms of education for maritime vocation. Despite the fact that the use of celestial navigation is a convention-regulated and required competency, not that many officers make use of it. This situation is possible due to excessive reliance on global navigational satellite systems [Ibanez, 2018]. The purpose of this paper is to analyze the legislative requirements, educational modules and teaching standards in celestial navigation, required education and also to show their deficiencies and advantages in terms of celestial navigation development, by showing different navigational problems and solutions concerning the topic.

Among literature, there is a certain amount of papers dealing with specific methods used to determine the position in celestial navigation, including modern solutions such as ECDIS (Electronic Chart Display and Information System), digital sextant, etc. However, we can say that minimal research is being carried out nowdays on the topic of what is the current and future meaning and role of celestial navigation in the maritime industry in terms of working skills and competencies, or as part of education for maritime occupations in the context of the need for future competencies required for work in the maritime industry.

So, to give a clearer perspective and insight on the topic in hand and matter which lacks in scientific literature the authors gave a review of the existing legislation concerning the STCW and IMO. Various studies were reviewed, as well as the most frequently used methods for determining the vessel's position using celestial methods. Finally, the most critical features of celestial navigation will be assessed as well as multiple other aspects by the use of SWOT analysis.

The article consists of 5 main parts, including an introduction and a conclusion. After the introduction, an insight into the existing legislation is given, followed by an analysis of the existing methods for determining the line of position, i.e. the position, and finally an overview of the advantages and disadvantages of celestial navigation.

2 OVERVIEW OF THE EXISTING LEGISLATURE

The reason why celestial navigation is taught in schools in a manner and through a syllabus laid down in the course is to be compliant with the current IMO/STCW legislature. Such legislature is comprised of the STCW which prescribes the minimum proficiency in Table A-II/1 and A-II/2 of the STCW Code for navigation and proposes that under required knowledge, understanding and proficiency the user must be able to obtain and determine a position by means of celestial observation, amongst others. The criteria for evaluating this competence must be a fix obtained by celestial observations within the accepted accuracy level. [STCW, 2017]

The most elementary subjects of celestial navigation course consist of but are not limited to, nautical astronomy, adjusting the sextant for adjustable errors, reading altitude, sight reduction computation, plotting lines of position, calculation of the time of meridian altitude of the sun, latitude by Polaris, determining of visible rising and setting of the sun, determining compass error by azimuth or amplitude and star identification and selection and determination of UT (Universal time) [STCW, 2017]. More details are available in IMO guides, like Model Courses 7.01&7.03 [IMO Model Course 7.01&7.03, 2014]. On top of that to be even more general when speaking about celestial navigation, one could argue that it can cover any of the methods which utilize observations of celestial bodies — bodies with known ephemerides as a standard celestial reference frame to determine the position [Dachev and Panov, 2017]. That means that determining the position in celestial navigation is based on direct measurement of height and/or azimuth of a celestial body(s), knowledge of predicted and measured data (nautical tables – almanacs – with data related to celestial bodies and their movement), chronometer, telling the time and knowing the error of the instruments used in measuring.

It is also worth mentioning that the STCW requires deck officers to present proficiency in celestial navigation, but under SOLAS Chapter V, Regulation 19 it is not required for vessels to carry a sextant onboard [Garvin, 2010]. And on that inconsistency, there is also a lack of consistency between the competencies related to celestial navigation that students are required to learn during their schooling period and those required in professional practice [Ibanez, 2018].

On that ground some IMO members have even made motions on reducing the requirements for celestial navigation education, some going as far as proposing to completely cancel it. For example, in 2008, in process of review and revision of the STCW, Norway proposed cancelling the celestial navigation course as a mandatory from the STCW Code [IMO STW, 2008a]. China proposed maintaining the obligatory requirements on knowledge and skills with respect to celestial navigation, the course to be simplified, i.e. to keep observations limited to the sun and stars, and to allow the use of electronic nautical almanac and celestial navigation calculation software. Also the United States didn't support the complete deletion of celestial navigation from the tables of competence, but the paring down of the requirements for celestial navigation knowledge to the bare essentials. The reasons was no back up for GPS (Global Positioning system) in ocean navigation [IMO STW, 2008b]. The Manila STCW amendments concluded that the convention would keep a need for professional competencies required for using celestial bodies to fix the vessels' position as an essential part of required skills. However celestial navigation may be left out for the issue of restricted certificates for working onboard on coastal voyages. In open sea navigation it is primarily used as a backup system for satellites [Ibanez, 2018]. It is also worth mentioning that the US supports moderating the celestial navigation requirements in terms of keeping it necessary in its backup navigation role and carrying out compass error corrections [Garvin, 2010]. In 1998, it was announced that students attending the US Naval Academy would no longer be taught to use celestial navigation as an important means of navigation. Instead, they proposed adding extracurricular hours for teaching computer-based navigation [Garvin, 2010]. The idea was finally abandoned.

The United Kingdom government also proposed/recommended much-needed changes in the IMO/STCW course for celestial navigation. Through their proposal to modernize the methodology of teaching, assessment and examination under the STCW courses for celestial navigation they made a clear distinction between recommendations for outcomes of teaching different parts of celestial navigation modules varying from the recommendation, firstly, to keep the essential module parts, such are the sextant handling techniques. Secondly to modernize different parts of the module due its methodical out datedness, and need for continual applicability. Such are predicting the time of twilight, meridian passage, sunrise and sunset, including the use of celestial navigation computer software, etc. Thirdly, to remove some parts which are thought to be obsolete. [Gov.UK, 2023]

But when talking about education some research [Garvin, 2010] shows that the traditional, existing or most commonly used methods of celestial navigation are thought by students as somewhat challenging in terms of the nomenclature. The mathematics involved is what is usually pointed out as challenging for some. To bring traditional methods and modern technology closer together, some suggest a form of media that is highly visual and easily customisable, e.g. Google Maps [Bensky, 2017]. Solutions like this enable very easily showing the GP (Ground Position) of the celestial body and the COP (Circle of position), and finally the fix as intersection of two or more COPs.

However, despite some efforts attempted at certain universities and academies little improvement was done in eliminating or changing the perception students have about celestial navigation. Moreover, celestial navigation teachers, nowadays more than ever, face the challenge of teaching a subject thought of as difficult and even as outdated. However, once students finish their education, it is likely that they will no longer use the sight reduction practice to fix the vessel's position, as it is not standard practice on board a vessel [Ibanez, 2018].

3 EXISTING, MOST COMMONLY USED METHODS AND MODERN SOLUTIONS

Like all other forms of navigation, celestial navigation has its historical development and progress, which through the passage of time and the development of scientific and technical disciplines enabled and led to the emergence of new methods that are adapted to the acquisition of new devices and knowledge.

The most elementary equipment used for celestial navigation are the instruments for vertical angle measurement (sextant), time measurement (chronometer) and compass with bearing sight. Of course, known ephemerides of the celestial bodies are also required, i.e. nautical almanac.

Dachev and Panov (2017) group various celestial navigation methods into three categories:

- Traditional, manual methods, based on the use of a handheld sextant, manual sight planning and reduction procedures (i.e., printed almanac and forms);
- Traditional, computer-based methods, require the use of the sextant, but sight planning and reduction are performed using software;
- Fully automated methods, such as the use of an automatic electronic sextant, or star-tracking systems with automatic sight reduction.

But, when speaking about the present celestial navigation, the intercept method (Figure 1) is considered the most common method which is used onboard today, it is also known as the Marcq St. Hilaire method, very well described in navigation books and manuals [Coolen, 1987], [Bowditch, 2002], [Astro navigation, 2017] [Burch, 2021], etc. Amongst other methods are the Dozier (direct) method [W.Gery, 1996] [Ruiz, 2008] and some of the long-standing methods such as the Sumner line of position [Bensky, 2022], longitude methods and the ex-meridian method [Čumbelić, 1990], [Lipovac, 1981], [Lušić, 2017].

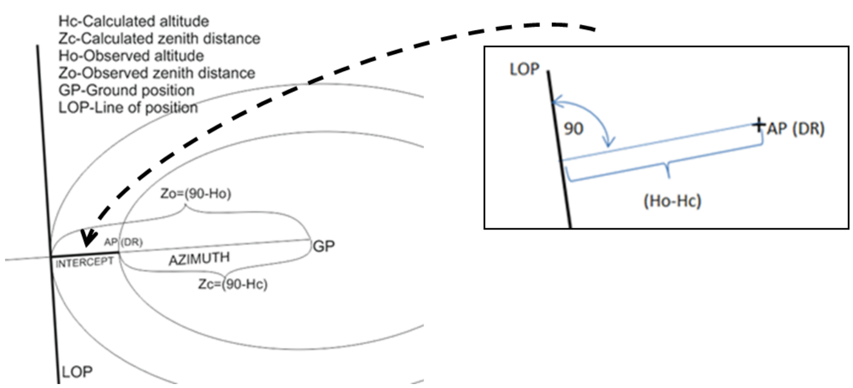

Figure 1. Concept of the Intercept method-line of position (LOP) drawing
Source: [Lušić et all, 2018]

Some methods only require precise measurement of the azimuth, that meaning for which the sextant is not needed. Such a method is based on fixing two positions close to the dead reckoning position and lying on the isoazimuthal curve, i.e. a curve of the same great circle azimuths of a celestial body [Lušić, 2017]. However, the problem with azimuths is the impossibility of precise measurement, at least not with a standard diopter [Nguyen et all, 2016] [Lušić, 2017]. Problem of azimuth is also in methods based on use of single body, i.e.

vertical angle in combination with the azimuth. Method is well known but rarely used in practice [Lipovac, 1981], [Soung, 2020], [Wei, 2015]. Position can also be obtained only with azimuths in a method based on using a converted formula of Newton's iteration method in a nonlinear system for working out the vessels' position. According to the K. H. Zevering, the positioning methods based on intersection of two position circles can be divided on the intercept method, its more novel the least-squares method and the double sight or two-body method, but as observations in celestial navigation are almost always sight-run-sight cases (running fix) it is recommended to use GHA (Greenwich Hour Angle) - Dec (Declination) updating technique, i.e. transferring the position circle on earlier (or later) sight [Zevering, 2006].

Practice and other studies show that due to possible overreliance on electronic navigational aids (with an emphasis on the word aid) Global Navigation Satellite Systems (GNSS) and particularly GPS have these days become the primary sources for fixing a vessel position in ocean navigation. Additionally, such aids and instruments are connected to almost all navigation equipment on the bridge [Ibanez, 2018]. So, on the trail of such navigation practice, research is trying to bring the methods of astronomical navigation closer to technology and above all to the digitalization of overall navigation and navigation equipment that is used both on board and to teach the celestial navigation courses at maritime schools. One of those aids is most certainly the ECDIS. However celestial navigation methods have not been foreseen by many EDCIS makers, so that's why most current ECDIS systems do not feature the ephemerides and the possibility of direct positioning by using celestial bodies. Possibilities such as drawing lines and circles enable the graphical positioning of LOPs (line of positions) and, accordingly, positioning using the classical intercept method [Lušić, 2017], which leads us to believe that this will be an area of possible future development. Figure 2 shows how to use GIS (Geographic information system) to obtain celestial fix and how the proposed method can serve as a reference for the development of a celestial positioning module within the ECDIS [Tsou, 2020].

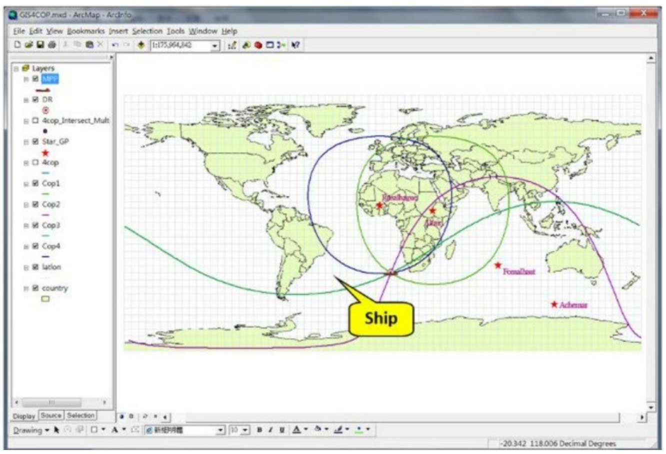

Figure 2. Multi-body celestial fix in the GIS environment
Source: [Tsou, 2020]

Figure 3. Fix by use of Manual Fix Position-Transas ECDIS
Source: [Lušić et all, 2018]

Figure 4. Digital sextant
Source: [The digital sextant]

So, the most desired modern solution would be to upgrade ECDIS to solve problems in celestial navigation or its integration with specialized celestial navigation software. Even today's ECDIS allow the drawing of various lines and circles that can be used to plot LOP (by intercept method) or circle of position (circle of equal altitudes) (Figure 3), or even to plot azimuths of celestial bodies directly (Figure 5) [Lušić et all, 2018]. In addition to the existing functions of ECDIS and its possible integration with specialised software for calculating celestial navigation, the use of modern aids such as the digital sextant (Figure 4) and aids with artificial horizons and star tracker systems should also be mentioned.

Figure 5. GP plot and use of azimuths to GP on ECDIS (Transas) to obtain fix
Source: [Lušić et all, 2018]

Some countries, more precisely, their naval services, in this example the US, have already developed different types, and over time, different generations of different systems using celestial navigation. Such systems include but are not limited to the strategic missile systems such as Polaris, Poseidon, Trident, and MX, all of which have used star trackers to determine the absolute orientation of the vehicle for the inertial guidance system. Most modern units can achieve sub-arcsecond angular precision [Gregerson et all, 2000]. Although these systems differ one from another it has been shown how star tracking systems are the most practical option for the above purpose. The new star trackers are simpler, smaller, draw less power, and more reliable, when compared to the old technology. With higher quantum efficiency detectors, many more stars (thousands rather than tens) can be observed, providing a substantially higher data rate [Gregerson et all, 2000].

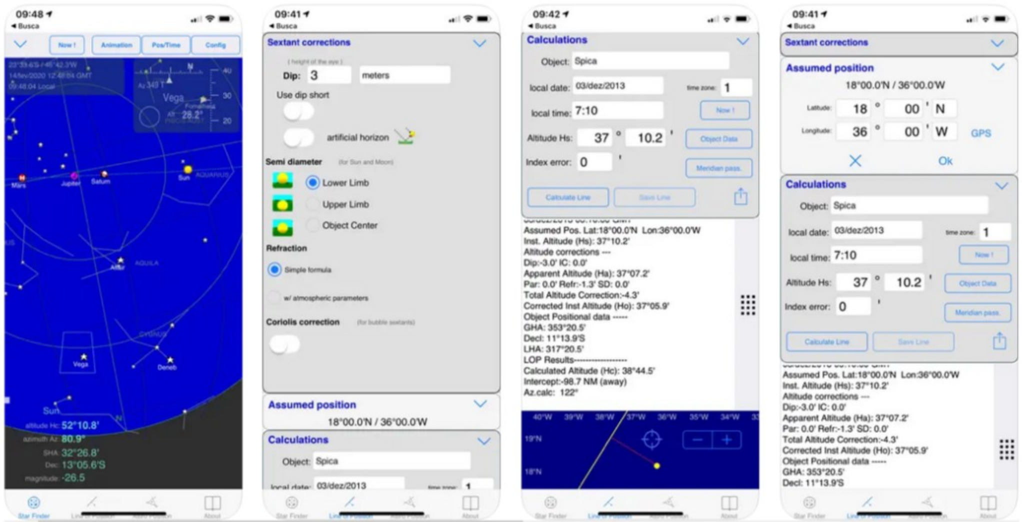

Figure 6 a). Celestial navigator software ''Celestial navigator''for cell phones
Source: https://apps.apple.com/us/app/celestial-navigator/id696927722?platform=iphone

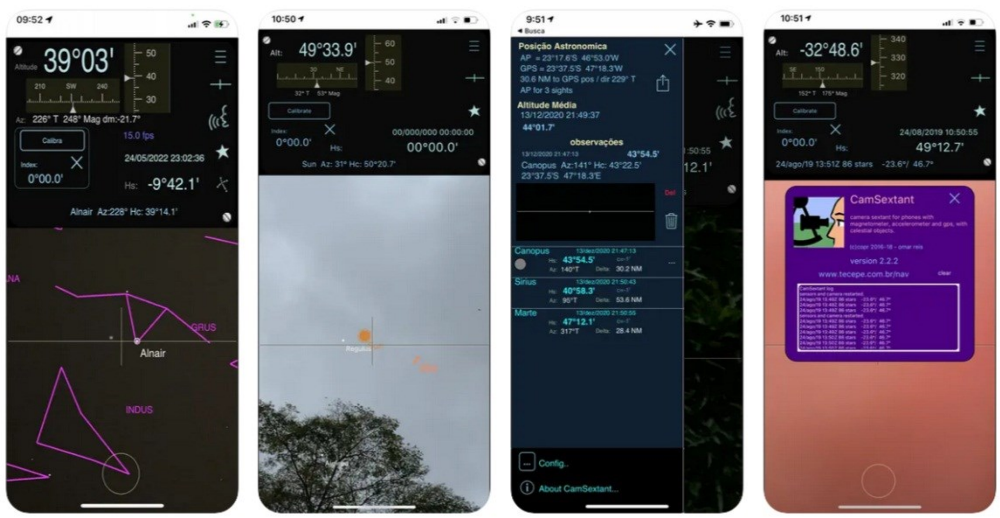

Figure 6 b). Celestial navigator software ''Camsextant'' for cell phones
Source: https://apps.apple.com/us/app/camsextant/id1076411081

A pragmatic approach is being taken in making use of smart devices such as smartphones (Figure 6), tablets, pocket PCs, and other devices that have very powerful sensors for orientation. Such devices are used for obtaining orientation measurements in all three axes and are used as celestial navigation measurement devices to measure the orientation angles of celestial bodies to replace traditional measuring devices such as sextants [Grm and Grm, 2021]. Research varies from replacing or using different measuring devices to efforts for a completely different novel method based on high technology systems. A method, which until recent years would be considered quite futuristic, is proposed for fixing a vessel position by using naturally appearing pulsar signals as an alternative to the use of the sextant. The use itself is made out of four particular pulsar radio signals whose timing reoccurrences are comparable to atomic clocks and whose characteristic signatures can be used as radio navigation beacons [Adamson, 2022].

4 ADVANTAGES AND DISADVANTAGES OF CELESTIAL NAVIGATION

As it is clear from different efforts, nationally or internationally, there is more and more dispute about celestial navigation and its role and position in the future environment of the maritime navigation. Questions asked on that topic have to do with whether or not it should be taught at schools, whether or is it a needed competency of a future seafarer, and what is the future of its role onboard vessels. In attempting to answer such a question, one must address a few items concerned with the topic at hand. Admittedly one of the most independent and reliable techniques of positioning is certainly celestial navigation, due to its long-lasting proven success in use where a set of mathematical laws that, from the correct change in the position of celestial bodies, enable orientation on the open sea [Klarin, 2007]. The purpose of education and study of celestial navigation in maritime teaching institutions has been to provide future seafarers with needed professional competencies, thus enabling them to fulfill their responsibilities as deck officers. In addition to enabling them with competencies, it should also make them more confident in their navigating abilities [Garvin, 2010]. Of course, the industry, the techniques, all that which goes along with it, are progressing and improving, but a general trend is the overreliance on all of those technologies. When looking at the bigger picture the only real alternative to existing GNSS systems is still celestial navigation. Some think that it should certainly stay that way because the philosophy of any good seafarer is to always have a reliable backup to anything, let alone means of navigation. One such example of when a much-needed backup navigational system is needed when sailing navigation in the circumstances of war events. GNSS liability implies a need for alternative means of fixing a position while out at sea, and the experts agree that celestial navigation is still suitable for such a purpose, since it is independent of the electrical supply [Ibanez, 2018]. Another thing that should make celestial navigation more attractive for shipping companies to implement celestial navigation on their ships is the low price and easy maintenance of navigational aids. Those aids, as all other aids, tend to be more developed in the future, therefore, simplifying the use using electronic aids which are, or are yet to be incorporated, that way giving officers who are already overloaded with their daily work a chance to perform celestial navigation while saving time. With aids improving in the future, this would lead to improvement of system integration and development of future military and commercial technologies for celestial navigation, application of modern electronic aids and specialized software and development of systems for automatic tracking of celestial bodies and related positioning.

Undoubtedly celestial navigation is not perfect, its position accuracy is not always that high, the measurements depend on hydro meteorological conditions, meaning the weather, sky cover, horizon visibility, and whether or not it's day or night. Celestial navigation is often overlooked as an alternative to GPS. This is mainly due to the fact that it requires working with a sextant and using an almanacs, knowledge of the sight reduction method and knowledge of relatively complicated mathematical equations [Garvin, 2010]. It's even sometimes described as being complicated and/or demanding in terms of its methods, time consuming, for many obsolete in its essence. But the greatest threat concerning celestial navigation is its very removal from STCW as a mandatory competence.

Apparently there is a lack of easily adaptable visual methods for demonstrating the basic ideas and concepts. Part of the researcher's effort is to take the traditional celestial navigational techniques and develop a more modern and simplified set of examples that can appeal to today's seafarers, and students. The aim of teaching celestial navigation has always been a simple one: that students – future deck officers - are aware of the fact that objects "*in the sky*" can be used to determine the ship's position. However, students sometimes believe that the practical use of a sextant is merely an "*old fashioned*" version of a GPS, even though both are used for obtaining the position fix [Bensky, 2017]. Teaching celestial navigation must adapt to the future, and adapt the syllabus in duration and contents, removing complexity from the definition of its foundations and reducing the methods and problems to the necessary minimum [Ibanez, 2018].

The attached SWOT analysis (Table 1) identifies the key strengths, weaknesses, opportunities and threats of celestial navigation. Of all the advantages mentioned, we can point to the numerous opportunities that modern technology offers to maintain astronomical navigation as a practical and cost-effective alternative to modern positioning systems.

Table 1. Analysis of celestial navigation advantages and disadvantages

Strengths	Weaknesses	Opportunities	Threats
- Independent and reliable positioning - The only real alternative to existing satellite positioning systems - Low price and easy maintenance - Simplified use using electronic aids	- Low position accuracy - Dependence on weather, sky cover - Time of day, visible horizon - Lack of celestial bodies during the day - Instruments imperfection - Complicated and demanding methods - High price of new (alternative) systems	- Improvement of system integration - Improvement of ECDIS - Development of military and commercial technologies - Application of modern electronic aids and specialized software - Development of a system for automatic tracking of celestial bodies and related positioning	- Development of alternative positioning systems (satellite, hyperbolic, inertial, ...) - Removal from STCW as a mandatory competency - Fully autonomous vessels''

To summarize, celestial navigation is a viable tool whose application should not be only at maritime education institutions. A possible part of the solution is that different conventions, inspections and company policies require their officers to perform some form of celestial navigation daily. Instead of trying to remove or minimize required competencies for celestial navigation maybe there should be consideration for increasing it. Modern solutions and the use of electronic devices and aids should also be acceptable. No matter what the future decision is, the fact is that there cannot be one without the mutual consensus among countries which is needed to maintain the effort of the IMO and its conventions on trying to standardize, uniform the system of education and give the proper foundation for acquiring the needed competencies.

5 CONCLUSIONS

For centuries celestial navigation was the main method of orientation of sailors in ocean navigation. At the beginning of the development of electronic navigation, celestial navigation confirmed its status as one of the most reliable methods for checking data, most importantly vessel positions obtained with electronic instruments. So, when considering the importance of celestial navigation, in the context of existing positioning systems at sea, studying it within the terms of it being a part of a mandatory content at maritime colleges is completely justified, understandable and necessary. Namely, on the open seas, almost the only alternative method of positioning to satellite positioning systems are the celestial navigation methods, at least today on most merchant ships. On the other hand, the increasing use of automation, the development of autonomous vessels and technological development in general, results in a tendency to neglect or minimize the importance of classical navigating skills. Thus, making classical navigation methods are perceived by many as obsolete or ineffective, from what is understandable that some try to remove its contents from the school curriculum. Nevertheless, it should be considered that the mentioned progress enables solving positioning problems with the help of celestial bodies simpler and faster than never before, not to mention that it can ultimately make it available "one click away". Even with all of the alternative (electronic) positioning systems and methods put into use in the context of global navigation satellite systems, celestial navigation methods may remain as a last resort. Therefore, there lays a need for it to be studied as a part of the formal system prescribed as future seafarers' education. In the end, knowledge of the basics of celestial navigation, whose importance is particularly evident in the safety aspect of navigation and ship management, orientation and navigation in space with the help of celestial bodies belong to classic nautical skills and should remain as such.

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