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CELESTIAL NAVIGATION AS THE EMERGENCY GNSS BACKUP: ENHANCING NAVIGATIONAL RELIABILITY

Ihor Liubarets
State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, Ukraine,
Faculty of Navigation, e-mail: Ilyubarec@gmail.com
ORCID 0000-0003-1810-1435

Abstract: The development of Global Navigational Satellite Systems (GNSS) has revolutionised navigation on ships. GNSS, together with electronic chart display information system (ECDIS), has made navigation more accurate, efficient, and safer for sailors. However GNSS signals can be affected by various factors such as spoofing, jamming, ionospheric disturbances etc., while no backup means of position fixing in the open sea are available on board ships. Over-reliance on GNSS without the development of an alternative backup will jeopardise safe navigation of ships. However, most of the alternatives available are either complicated or expensive. By changing certain regulations and further development celestial navigation, a reliable and cost-effective backup system can be obtained.

Keywords: Celestial fix, ECDIS, GNSS, Safety of Navigation.

1. INTRODUCTION

The political situation in the world today is characterised by uncertainty and volatility. Many countries are facing significant challenges related to political instability. There are several ongoing conflicts and crises in many regions, including Europe, the Middle East, Africa and Asia. The conflicts start in the cabinets of politicians and continue on the battlefields. The modern battlefield is highly dependent on precise positioning, navigation and timing, which are provided by GPS, GALILEO, GLONASS and similar systems. Nowadays, all that needs to be done is to leave the enemy without a satellite signal; without exact positioning, he will become extremely vulnerable. So, satellite navigation systems have become a strategic advantage to the country using them and a strategic target for the enemy.

In 2018, Russian GPS jamming disrupted a NATO exercise in Scandinavia. Moreover, Chinese GPS spoofing signals can cause ships in many coastal areas to see false locations. There are concerns about whether the satellite system might be hacked or the satellites themselves knocked out by an enemy or a massive solar storm. This would severely affect the safety of navigation, especially as far as merchant ships are concerned [Popular Mechanics 2021]. Then navigating officers would face the problem of knowing the exact position of the ship. Unfortunately, alternative electronic navigation systems such as Omega have been decommissioned and long-term operational support for others, such as LORAN-C, is not guaranteed.In any event, LORAN-C is not available worldwide. Inertial navigational systems are relatively expensive. The cheaper ones still depend on satellite signal [Frost 2023]. Thus nowadays, in case of GNSS failure in the open sea, the only available method of obtaining the ship's exact position is the celestial plot [Vulfovich and Fogilev 2010].

There have been many methods devised in the past for obtaining position information from astronomical observations. Most of them have been devised with the quickest possible solution in mind. Many have been in tabular form to reduce the amount of calculation required for the navigator, and these have been known as short method tables or sight reduction tables. Before the introduction of the ubiquitous handheld calculator, a logarithmic solution was used, and the haversine formula was best suited to this method. With the availability of calculators, the importance of 'short method' tables has decreased and the haversine formula is no longer the most convenient one for manual solutions. It may be said that the quickest way of producing a result during manual calculations is using the fundamental spherical cosine formula and the intercept method (Marcq St. Hilarie Method) [Frost 2023]. Using this method involves plotting the calculated position lines on the chart or on a Mercator plotting sheet. Before plotting the position lines. they have to be calculated and the observed altitude with bearings of the objects must also be measured. This requires the navigator to have a certain degree of training and experience. Unfortunately, not so many watch officers have the required degree of experience for this [Garvin 2010]. Fast growing digitalisation, together with the increasing accuracy and availability of GNSS navigation, have led to navigators becoming too reliant on electronics.

2. PROBLEM

The problem of the absence of an alternative source of position in the open sea other than GNSS is much more serious that it appears to be. The seamless integration of electronic position fixing and electronic charts within ECDIS has transformed modern navigation practices. However, instruments for terrestrial position fix on many ECDISs (in spite of their common awkwardness), are quite reliable and can be very efficient in the hands of a well-trained operator [Leedham Marine Consultants Limited 2023]. Modern radars, precise gyrocompasses and azimuth circles allow the navigator to measure values and to plot observations quickly and accurately. However, as far as instruments for celestial navigation are concerned, the situation is quite different. First of all, more instruments are needed for a celestial position fix than for a terrestrial fix. These instruments are: sextant, Nautical Almanac, Azimuth circle, gyrocompass, stopwatch, chronometer, calculator, plotting instruments, celestial globe or star finder, nautical charts or Mercator plotting sheets. Even if one item from the list is not available, a celestial position fix will be impossible to perform. The gyrocompass, azimuth circle and nautical almanac are compulsory items required by regulations [SOLAS 2020]. Stopwatch, navigational calculator and plotting instruments are common instruments in a ship's stationary. In the worst case scenario, any smartphone can replace a stopwatch and calculator. Star finders or celestial globes are not really necessary if the officer has a good knowledge of celestial navigation. However, there are problems with the sextant, chronometer, nautical charts and Mercator plotting sheets.

The sextant had been a compulsory nautical instrument on board ships since people discovered it and until GPS was widely implemented. Today, the sextant is not mentioned in the list of compulsory navigational equipment in SOLAS. There is no legislative regulation regarding this instrument at all. This gives ship owners the right not to supply sextants on board. Many shipping companies try to cut the final cost of the vessel as much as possible during delivery of the new vessels. They try to comply just with the minimum requirements of the regulations, and they have the right to do so, as they are still not breaking the law. Nevertheless, there are companies which still supply each new ship with a pair of sextants, chronometer, celestial globe and a so called emergency chart folio in paper format [Own experience]. Such companies, at least, do not cause their seafarers to break the requirements of the STCW Code Section A¬ II/2 and Section A-II/2 which, incidentally, require officers of the watch to show proficiency in celestial navigation [STCW 2017].

This same issue applies to chronometers. Today, many seagoing ships no longer have chronometers on board due to highly accurate time signals provided by GPS [The Nautical Almanac 2017]. There is simply no regulation that obliges all ships to have chronometers on board.

In addition to the above paragraphs, in July 2022, the United Kingdom Hydrographics Office (UKHO) announced its intention to discontinue the production of paper charts. Following consultations with the Maritime and Coastguard Agency and national user groups, the UKHO set a target date of late 2030 [GOV. UK 2023].

Facilities provided in most ECDISs' systems for plotting even terrestrial position lines are often awkward to use, time consuming and counter-intuitive. It would appear that they were given a very low priority at the initial concept and software design stage, and this has not improved with time [Leedham Marine Consultants Limited 2023]. Moreover, only positioning by plotting lines of position (LOP) using the traditional intercept method (IM) is provided, while celestial positioning methods are not implemented at all [Tsou 2020]. Thus, nowadays only Mercator plotting sheets and paper charts would be able to provide an effective and accurate celestial plot, and in the near future, paper charts will be withdrawn. With

Mercator plotting sheets, there is the same problem as with the sextant and chronometer: the absence of any regulations requiring their carriage.

The use of ECDIS definitely has many advantages over paper charts. The positive aspects of ECDIS are: easier voyage planning, simpler chart correction, continuous monitoring of depth safety contours and soundings and readily available information when approaching ports or busy navigational areas. On the other hand, the integration of electronic position fixing and electronic charts in ECDIS inevitably implies a high degree of reliance on its electronic position fixing sources. Unfortunately, as mentioned above, these sources are extremely vulnerable.

Where interference is encountered on the GNSS frequencies, whether by natural events such as space or weather; accidental events such as faulty equipment, or an intentional act, a GNSS receiver is, under such circumstances, rendered unable to maintain a lock on the satellite signals. In general, accidental and natural signals are termed interference, while deliberate events are termed jamming. GNSS interference and jamming have the potential to stop the vessel's GNSS receiver from reporting the correct position, as it cannot track and decode the data from the GNSS satellites. Jamming, on the other hand, is signal interference that limits the receiver's ability to successfully receive the desired GNSS signals. Spoofing is the providing a fake signal to generate a false position and time in the GNSS receiver. A spoofing incident generally starts with a jamming signal that causes the vessel's receiver to lose the lock on real GNSS signals and move to the stronger, spoofing signal [United Kingdom Hydrographic Office 2020]. The jamming will be immediately indicated by an alarm from the GNSS receiver. The problem with spoofing is that it is quite difficult to recognise a false position and time given by the GNSS receiver in time. The GNSS receiver continues to receive a signal which is absolutely false.

If a GNSS back-up were available on board (in the form of LORAN-C, an inertial navigational system or celestial fix), it would be possible to continue safe sailing. The ship's position would not be as accurate as that obtained from the GNSS receiver but good enough for safe sailing in the open sea. The availability of a chronometer on the bridge would have allowed the navigator to find out quite a precise time. Unfortunately, less and less ships usually provide the opportunity for alternatives to the GNSS signal source of a ship's time and position.

In summing up, it seems that there are a continually increasing number of ships with no sextant, no chronometer, no charts and no Mercator plotting sheets on their navigational bridges. Even if certain shipping companies provide sextants and chronometers, by 2030 paper charts will no longer be available . Then, if regulations are not changed, the only available ways of providing an alternative source of position in the deep sea will be the sextant, chronometer or Mercator plotting sheets. Moreover, none of these are mentioned in the international regulations as a compulsory item on board. Considering ship owners always try to comply with the minimum requirements of regulations in order to save money, there will be a considerable amount of ships with navigators relying exclusively on satellite navigation while sailing in the open sea, which can significantly endanger all maritime traffic. This is due to increasingly frequent deliberate GNSS hacking and attacks.

3. RECENT PUBLICATIONS CONCERNING OF THE FUTURE OF CELESTIAL NAVIGATION

Scientists all over the world have started to work on this dependency on shipboard electronic navigation, since this type of navigation has been widely introduced. The Master's project "Future of Celestial Navigation and the Ocean-Going Military Navigator", prepared by Michael J. Garvin under the direction of Dr. John M. Ritz in OTED 636, comprises a questionnaire conducted using the descriptive method to gather and analyse data collected from the U.S. Army Transportation Corps Marine Deck Warrant Officers. As a result of this research, the author suggests a need to incorporate electronic navigation, navigational calculators and computer programs into the celestial navigation curriculum, to keep it viable in a technologically changing world. The data collected during this study also suggested revising the celestial navigation requirements, lowering the examination pass scores for students studying navigation, and permitting solutions by navigation or programmable calculators [Garvin 2010].

An article "New Ideas for Celestial Navigation in the Third Millennium" by Boris Vulfovich and Vasily Fogilev reports on innovative mathematical and analytical approaches to celestial navigation [Vulfovich and Fogilev 2010]. It is stated that defense forces are increasingly reliant on GPS, and it is important that this dependency does not become a single-point-failure risk for maritime safety. Independent alternatives to GPS are urgently required. Imaginative application of the available technology can ensure that celestial navigation has as much of a role to play in the future as it has had in the past in helping to provide safe passage for seafaring worldwide.

"Using GIS to Obtain Celestial Fix under the Framework of an ECDIS System" by M.C. Tsou proposes a simple method for obtaining a celestial fix, developed within a Geographic Information System (GIS) under the framework of an ECDIS system. The underlying principle is dependent on the most fundamental theory in celestial navigation; the circle of position (COP) of the celestial bodies is plotted to find the fix [Tsou 2020].

Finally, the article by G. Grm and A. Grm "Testing the Functionality and Applicability of Smart Devices for a Handheld Celestial Navigation System" exposes the problem of a celestial fix obtained with smart devices but without the need of visible horizon. The idea is to replace the sextant with a smart device to measure the altitude and possibly the azimuth of the celestial body. Estimates of the position error by the graphical method were in the range of 10 Nm to 30 Nm.

In the paper, it was stated that a fully functional system could be considered as a cheap off -the-shelf handheld Celestial Navigational System (CNS) [Grm and Grm 2021].

4. POTENTIALLY EMERGENCY GNSS BACKUP SYSTEMS

4.1. Radio navigational systems

Radio navigation systems have been a crucial part of maritime navigation for many years. They provided ships with the means to determine their position and navigate safely at sea. For example, LORAN (Long Range Navigation), initially developed during World War II for military navigation near the American coast, saw significant advancements in the 1950s when Loran-C was introduced. Loran-C offered greater accuracy and extended range (over 2,000 miles) for civilian use. So, the original LORAN system (Loran-A) was replaced by Loran-C.

Loran-C operated in the 90–110 kilohertz range and expanded its coverage to encompass most of the continental United States, Canadian waters, and the Bering Sea through international cooperation with Canada and Russia [Jansky and Bailey for the US Coast Guard 1962]. Many other countries also developed similar LORAN-like systems. While LORAN-C remains in use on some aircrafts, its precision, typically within 10 metres, falls short of the accuracy provided by satellite-based navigation systems like the Global Positioning System (GPS). As a result, land-based navigation systems like LORAN appeared to be phased out in modern navigation, with GPS being the primary choice for precise and global positioning. LORAN stations were not available everywhere, and coverage was limited to specific regions. This made it less useful for global navigation compared to GNSS. Also LORAN was less susceptible to jamming than some other systems, it could still be affected by atmospheric conditions, electromagnetic interference, and other sources of noise, which could reduce its accuracy. LORAN technology is considered outdated and has largely been decommissioned in many regions. As a result, finding compatible equipment and support for LORAN can be challenging.

Operating and maintaining LORAN equipment required specialised training and knowledge; modern navigation systems like GPS are more user-friendly and accessible. In summing up, LORAN has become obsolete due to the widespread adoption of GNSS, which offers greater accuracy, global coverage, and greater user-friendliness [The Nautical Almanac 2017]. While LORAN-C is considered to have become outdated, enhanced LORAN (E-LORAN) has the potential to become a prospective system for further development and implementation, despite unavoidable maintenance difficulties and high implementation costs [Public Law 115–282 2018]. Apparently, it will be too expensive to resume its functioning for the purpose of GNSS back up.

4.2. Inertial navigational systems

Inertial navigation has emerged as a distinctive method for navigating without reliance on external sources of information. Unlike conventional navigation methods, inertial navigation operates in a relative sense, continually updating a moving ship's position based on its initial navigation state. This inherent self-sufficiency makes inertial navigation systems impervious to jamming and spoofing, rendering them invaluable in various applications [Naser and Youssef 2020].

Over the years, inertial navigation systems have significantly evolved from their inception in the 1940s to their current state. Recent advancements have seen inertial sensors transition from purely mechanical to incorporating diverse technologies, harnessing various physical phenomena to accurately compute dynamic forces acting on moving bodies. This evolution has shifted from complex stable-platform inertial navigation systems to computationally intensive strap-down inertial navigation systems [Noureldin, Karamat and Georgy 2013].

However, inertial navigation systems also come with challenges related to calibration, drift, cost, and susceptibility to motion-induced errors. Combining inertial navigation system with other complementary navigation technologies (e.g. GNSS) is still necessary to help address some of these limitations and enhance overall navigation performance [Inertialsence 2023].

4.3. Sliced-lens star tracker

A celestial navigation system (CNS) called Sliced-lens star tracker has recently been patented by scientists at Draper Laboratory. In essence, a star tracker is an optical device used to determine a vehicle's position by measuring angles to known celestial objects, such as stars. It relies on a catalogue of these celestial objects and their precise positions in the sky. The star tracker typically projects the image of these objects onto a light-sensitive sensor array using a lens. In its early form, this system can achieve 50-metre accuracy in GNSS-denied environments, and what is really important is that it is possible to use a star tracker during the day (if the sky is not obscured by fog or clouds) [US 2019 / 0033421 A1 2019].

An innovative star tracker enhances celestial navigation technology in several ways. It employs smaller and lighter optics compared to traditional lenses, resulting in reduced overall size and weight. This reduction in size and weight is achieved without sacrificing high angular resolution. The system incorporates a pixelated image sensor, a comprehensive database of celestial objects and a specialised processor to estimate the star tracker's position and orientation. The potential impact of this new star tracker is the development of a smaller, lighter, and possibly more cost-effective CNS.

In any event, the CNS systems seem to be a promising possiblity for the future. Unfortunately, for now they are too expensive to install on board ships due to their complexity. Therefore, their use is limited to weather conditions. In spite of their ability to determine a vessel's position during daytime, such systems will not work when the sky is obscured by dense clouds.

4.4. Handheld Celestial Navigation System

The paper “Testing the Functionality and Applicability of Smart Devices for a Handheld Celestial Navigation System” by G. Grm and A.Grm explores the feasibility of employing smart devices as measurement tools to determine the orientation angles of celestial bodies. Smart devices, such as smartphones, tablets, and pocket PCs, come equipped with powerful built-in sensors for orientation measurement in three directions: pitch, roll, and yaw/azimuth.

The study comprises two experiments: one testing the accuracy of smart device orientation sensors and the other exploring hands-free altitude measurements with systematic error control. The results showed that orientation sensors exhibited good accuracy but required signal averaging to filter out oscillations. Azimuth sensor accuracy is unpredictable, making it suitable for control or star identification. The hands-free altitude measurement concept may be successful when measuring a substantial number of celestial bodies, making it feasible to collect data on nearly all navigable celestial bodies above the horizon in a single night.

As a result, the study presents a promising low-cost handheld system for Celestial Navigation [Grm and Grm 2021].

The idea of the low-cost handheld system for Celestial Navigation is brilliant. It may be that such Systems for Celestial Navigation will be even cheaper than inertial navigation systems or terrestrial radio navigation systems. So far, more development and research is needed to make them a valuable navigational instrument. Further improvement of the system could be an application of infrared light technology in the lens. Then all stars above the horizon will be visible during daytime which enables celestial bodies to be observed not only during darkness but at any time, if the sky is not obscured by clouds and the horizon is visible of course [Science Mission Directorate 2016].

Nevertheless, widespread implementation of handheld systems for Celestial Navigation also requires a change in the regulations. Firstly, requirements and standards must be adopted. Then, authorities must be assigned for surveying, certification and approval of devices. All these processes require time and funding. Nevertheless, in the future, a handheld system for Celestial Navigation may become a reliable GNSS backup, especially with the use of infrared light technology. For now, however, a fair amount of research and study is still needed to develop fully functional devices for celestial navigation [Grm and Grm 2021].

4.5. Celestial Navigation

Modern ships are equipped with an array of advanced navigational tools, including a GPS receiver, radar, echo sounder and ECDIS. These technologies provide real-time, highly accurate position information, making navigation more efficient and safe. In an era of increased reliance on technology, celestial navigation provides an accessible backup, ensuring that ships can navigate safely in the open sea even in the event of GNSS hacking or malfunction. Celestial navigation is not as accurate as inertial navigation systems, terrestrial radio navigation systems or even a sliced-lens star tracker. It is entirely dependenton weather conditions and can only be used when the horizon is clearly visible. It also requires the navigator to possess certain skills and experience. At this point, it seems that all other systems are much better candidates for a GNSS emergency backup.

However, celestial navigation has one huge advantage over other systems: it is cheap as it does not require expensive equipment, and there is no need for a global change of regulations to make it a compulsory emergency GNSS backup.

All the procedures and requirements of celestial navigation are already described in nautical almanacs, and seafarers have been using them for centuries. For example, assuming inertial navigation systems will be chosen as a compulsory emergency source of position on board ships, several regulations must be adopted: these include regulations regarding requirements for inertial navigation systems; regulations regarding maintenance of inertial navigation systems and regulations regarding training navigators to operate and maintain inertial navigation systems, etc. It is obvious how complicated this will be for the legislative institutions, shipping companies and maritime authorities. Furthermore, there will also be installation and maintenance costs for the inertial navigation systems. The same applies to terrestrial radio navigation systems and star trackers.

One hundred years ago, all ships in the open sea relied exclusively on celestial navigation. Gyrocompasses, radars and other equipment were far less precise and reliable than those available today. Nowadays, celestial navigation no longer seems crucial for shipping.

However, with the help of technologies and minor changes to regulations, it may become a cheap and legal emergency GNSS backup, enabling navigators to avoid being lost on the bridge when their GNSS is out of order. The navigators will continue their sailing using dead reckoning and by making celestial fixes whenever possible until land is reached.

5. CELESTIAL NAVIGATION AS THE EMERGENCY GNSS BACKUP

5.1. Necessary regulations concerning celestial navigation

First of all, it is expedient to refer to the legal side of the issue. As it mentioned in the introduction, a sextant and chronometer are not required by international regulations at all. Despite this, certain countries (e.g. New Zealand) still require the presence of the sextant and chronometer on the bridge for ships sailing under their flag [Maritime New Zealand 2019]. Unfortunately, the regulations that apply in certain countries cannot prevent the slow degradation of celestial navigation worldwide. The withdrawal of paper charts announced by UKHO will worsen the situation even more. Having the sextant, nautical almanac, calculator, chronometer, plotting instruments and paper chart on board is enough to perform a celestial fix. A Mercator plotting sheet may also be used instead of a paper chart. On the other hand, carriage of such sheets is not required by international regulations. Therefore, first of all, a regulation that obliges all ships sailing in the deep sea to carry a sextant, chronometer and Mercator plotting sheets should be introduced.

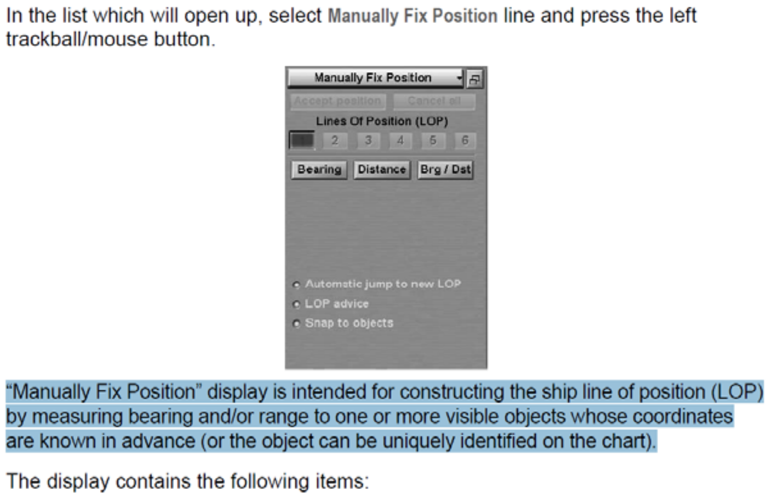
Another useful addition would be to clarify the regulation for Section A II/2 and Section A-II/2 of the STCW Code.. The regulation might require watch officers to check the GNSS position of the ship by means of a celestial fix, whenever possible, in the open sea. By complying with such regulations, the ship’s navigators will maintain their knowledge and skills of celestial navigation. In other words, they will be more prepared for situations in which the GNSS receiver suddenly appears to be unreliable.

5.2. Celestial fix plugin for ECDIS

As soon as paper charts are withdrawn, there will be only one possibility to perform a celestial fix using Mercator plotting sheets, which are not required by SOLAS or any other regulations. The reasonogic is simple: if they are not required by the law, their absence is not against the law. This will give ship owners the right to save costs by not providing them on board ships. It is necessary to understand that the final cost does not only mean the price of the item; it also includes delivery fees, warehouse storage etc. After the paper charts are withdrawn and no Mercator sheets are supplied, the navigator will only have ECDIS available for all kinds of navigation (terrestrial, celestial, satellite) [Leedham Marine Consultants Limited 2023]. With this in mind, it makes sense to view the newest and most popular ECDISs: FURUNO FMD-3200 [Furuno Electric Co Ltd. 2016], TRANSAS-NAVISAILOR–4000 [Transas Ltd. 2021] (Fig. 1), Sperry Marine Visionmaster FT ECDIS V. 5.1.0.5 [Northrop Grumman Sperrry Marine B.V. 2018], and JRC Jan-7201/9201

[Japan Radio Co. Ltd. 2021] (Tab. 1). However, none of these systems feature any instruments for a celestial fix.

Only in e-Globe G2 is a celestial fix actually mentioned. But unfortunately there is no instrument for making a proper plot, which must be done on the chart or plotting sheet separately, and only then can it be transferred to ECDIS, making this function absolutely useless [eGlobe G2 User's Guide 2016].



In the list which will open up, select **Manually Fix Position** line and press the left trackball/mouse button.

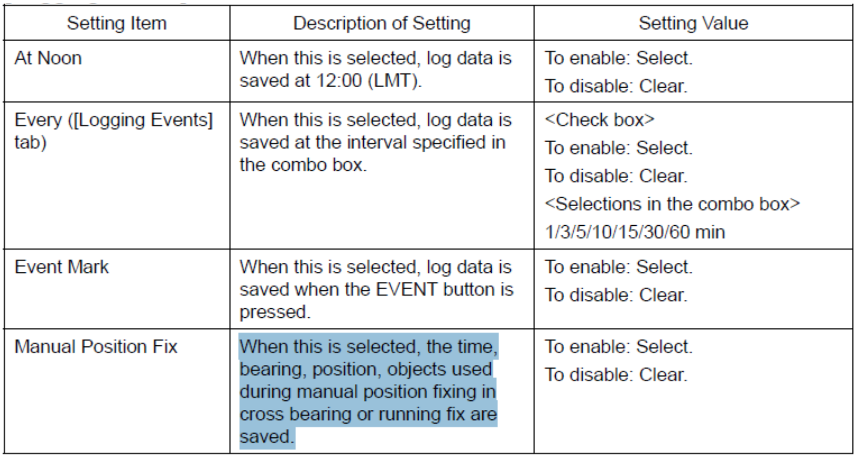
"Manually Fix Position" display is intended for constructing the ship line of position (LOP) by measuring bearing and/or range to one or more visible objects whose coordinates are known in advance (or the object can be uniquely identified on the chart).

The display contains the following items:

Fig. 1. Manual fix settings in Navisailor 4000

Source: [Furuno Electric Co. Ltd. 2016].

Table 1. Event log settings in JRC Jan-7201/9201



Setting Item	Description of Setting	Setting Value
At Noon	When this is selected, log data is saved at 12:00 (LMT).	To enable: Select. To disable: Clear.
Every ([Logging Events] tab)	When this is selected, log data is saved at the interval specified in the combo box.	<Check box> To enable: Select. To disable: Clear. <Selections in the combo box> 1/3/5/10/15/30/60 min
Event Mark	When this is selected, log data is saved when the EVENT button is pressed.	To enable: Select. To disable: Clear.
Manual Position Fix	When this is selected, the time, bearing, position, objects used during manual position fixing in cross bearing or running fix are saved.	To enable: Select. To disable: Clear.

Source: [Japan Radio Co. Ltd. 2021].

Even assuming that the sextant, navigational calculator and chronometer are available on board, a celestial fix will be still impossible to perform if there is no chart or plotting sheet. Moreover, even if charts and plotting sheets are available, a celestial fix is still quite a challenging procedure for the vast majority of navigators. According to Michael J. Garvin's research, the most difficult part of a celestial fix for deck officers and cadets is the calculation of elements of the celestial LOP and plotting. They would use celestial fix more often if it were easier [Garvin 2010]. The calculations that are required for the reduction of a celestial sight, if performed by hand, are slow and error-prone and discourage the human navigator from taking sights because of the tedious work involved. However, this changes if a reasonably accurate algorithm is implemented in a user-friendly program [Vulfovich and Fogilev 2010].

Modern ECDIS is a multitask instrument. A lot of bridge navigational equipment is integrated within it. NAVTEX and NAVAREA warnings are automatically plotted on the ENC [Furuno Electric Co. Ltd. 2016], and wind direction and force, main engine load and many other instruments are inputted into the systems. It should be a relatively straightforward task for ECDIS manufacturers to integrate the celestial navigation plugin in ECDIS like the Celestial Navigation Plugin for OpenCPN by Sean d'Epagnier [OpenCPN 2021]. The plugin is based on a computer assisted process. This is slightly different from traditional techniques as the Circles of Position are calculated using the Simbad database for stars and lunar, and the sight circles and intersections are neatly represented in the standard Opencpn interface [OpenCPN 2021].

In addition, there is also a Genetic Algorithm (GA) for solving celestial navigation fix problems (proposed by M.S. Tsou). GA is straightforward and its calculations are devoid of complex mathematical procedures. According to the creator,, the algorithm can potentially be integrated with ECDIS and can be effectively employed to determine a fix based on observations of a single celestial body (with multiple observations) or multiple celestial bodies, with improved results. Experimental outcomes underline that, in addition to bypassing cumbersome computation and graphical processes, the GA approach offers enhanced flexibility compared to other methods [Tsou 2014].

Today, there are several computer (PC) programs capable of performing a celestial fix within a few seconds. One example of this kind of program is ArcGis 10.5. Nevertheless, to make a celestial fix, the navigator has to use a PC, which means leaving his or her workstation to navigatie and maneuver simultaneously. After the celestial fix is obtained, it will be necessary to transfer the new position to ECDIS manually. Using an integrated program in ECDIS (e.g. Celestial Navigation Plugin for OpenCPN) will allow the navigator to perform a celestial fix within a short period of time, without leaving his conning position, which is highly important. Such a celestial position fix would require minimum time and skills and could be performed within a few simple steps.

The most difficult and time-consuming calculations and plotting will be done by computer within seconds. Such a plugin for ECDIS requires no changes to regulations; only minor changes to the ECDIS software are required. The plugin can make a celestial position fix much easier than manual calculations and plotting, now that it is known and used by navigators.

6. CONCLUSIONS

In today's uncertain and volatile political landscape, the need for satellite navigation systems like GPS, GALILEO, and GLONASS for precise positioning, navigation, and timing has become crucial for modern warfare and global trade. However, the vulnerability of these systems to jamming, spoofing, hacking, or natural disruptions poses significant challenges to maritime safety and security.

As a result, it is imperative to explore and implement alternative systems for emergency GNSS backup to ensure the continued safety of navigation at sea. Several potential solutions have been introduced in this article, including inertial navigation systems, star trackers, changing regulations, handheld celestial navigation systems, and the development of plugins for celestial navigation for ECDIS.

While technologies like inertial navigation systems, terrestrial radio navigation systems and star trackers offer potential solutions, they also involve various challenges such as high costs, changing regulations and maintenance. However, celestial navigation stands out as a cost-effective and readily available backup solution. It is based on traditional instruments like sextants, nautical almanacs, chronometers, calculators, and paper charts or Mercator plotting sheets. These instruments, when required by the relevant regulations, could serve as a reliable emergency backup.

To fully harness the potential of celestial navigation, there is a need for regulatory changes and industry adaptation. Key steps include:

- Regulatory Changes: International regulations should make the carriage of essential celestial navigation instruments, such as sextants and chronometers on board ships, compulsory.
- Training and Proficiency: Navigational training programs should be updated to ensure that mariners are proficient in celestial navigation, which will prepare them to use it effectively in the event of GNSS failure.
- Integration with ECDIS: ECDIS manufacturers should develop plugins or functionalities that seamlessly integrate celestial navigation into their systems. This would simplify the celestial fix process, making it more user-friendly and efficient for navigators.
- Research and Development: Ongoing research and development should focus on enhancing handheld celestial navigation systems and exploring innovative

technologies like infrared light to make celestial navigation more accessible and effective.

In conclusion, celestial navigation, as a reliable and cost-effective backup, is a very promising prospect for ensuring maritime safety in the face of GNSS disruptions and vulnerabilities. With the appropriate regulatory support and technological advancements, celestial navigation could play a vital role in maintaining safe global navigation.

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