The evolution of safe navigation: An overview of the technological advance through time

Dr. Chrysochou Georgios

Lt Commander. H.N., Lecturer at the Hellenic Naval Academy (HNA), Department of Combat Systems, Naval Operations, Sciences of the Sea, Navigation, Electronics and Communication Systems.

Abstract. This paper examines the evolution of navigation from antiquity up to date in the light of maritime safety and technology advances. Starting from the first navigational instruments, methods, and tools used for discovering the world, conquering new territories and exploiting the natural resources of both sea and land, the paper deepens in an analysis of the primary navigation safety concern issues that have been arisen in every era and the relevant solutions given in every case. Through this transit, the technological development of safe navigation tools and methods is highlighted, rendering possible for the reader to understand the foundation of modern satellite and electronic navigation. In this sense, the paper presents in a vivid way the latest developments in contemporary electronic navigation, concluding with a brief presentation of its prospects. It is worth to mention that all the efforts of the technological development have always been concentrating on resolving the issue exact time, both in classical and modern satellite / electronic navigation. This issue still remains considerable and not totally resolved since it has to do with achieving positioning precision at all times and circumstances.

Keywords: Classical Navigation, Electronic Navigation, Safety, Global Positioning System (GPS), Electronic Charts Display and Information Systems (ECDIS), Integrated Bridge Systems (IBS)

Introduction

Marine Navigation is the science of directing a vessel way to the desired destination by determining its position, course, and distance traveled. The first mariners who started their voyages at seas to explore new territories, gradually developed systematic methods of observing and recording their location as well as the distances and directions they traveled, by calculating the currents of wind and water, and potential hazards they encountered. Gradually, collision avoidance at sea became a concern, while modern navigation at sea has principally to do with a globally integrated transportation system. In this system each voyage from start to finish is concerned with core objectives, namely keeping the course, avoiding collisions, reducing fuel consumption, and conforming to the determined schedule. **[1]** So, obviously, marine navigation blends both science and art. Methods of navigation have changed throughout history, and the navigator must be the best ones to use. Among the main types of navigation we can list the following ones:

- **Dead reckoning (DR)**, which determines position by advancing a known position for courses and distances. Correcting the DR position for true course diversion, current effects, and steering errors, results in an **estimated position (EP)**,
- **Piloting**, which involves navigating in restricted waters nearby geographic and hydrographic features,
- **Celestial navigation**, which involves celestial measurements taken with a sextant, depicted after that in lines of position using almanac, nautical tables, calculators or even computer programs, or by hand with almanacs,
- **Radio navigation**, which uses radio waves to determine position with the aid of electronic devices. It is the application of radio frequencies to determine a position on the Earth.
- **Radar navigation**, which uses radar to determine the distance and bearing of objects whose position is known, and
- **Satellite navigation**, which uses radio signals from satellites for determining position. **[2]**

One could arguably state that radio, radar and satellite navigation constitute a broader category under the title **"electronic navigation."** Also, nowadays we could add one more type, to which the authors of this paper may attribute the title ***modern electronic navigation***. This type, which is characteristic of the contemporary technological achievements in navigation, is depended on electronic charts, related systems and integrated bridge concepts, commonly used as driving navigation system planning. With the advent of automated position fixing and electronic charts, modern navigation is almost entirely an electronic process. The mariner is constantly tempted to rely exclusively on electronic systems. Nevertheless, electronic navigation systems are always subject to defects, therefore the navigator must never forget that the safety of his ship might rely on skills related to classical navigation methods and types

Therefore, it is worth to examine how the methods and instruments of safe navigation have been developed throughout history and up to date so that the reader can realize the grandiosity of this form of combined art and science, which has made and continues to make our world more globalized and interconnected. In that perspective, the aim of this paper is to highlight, from a historical and maritime science point of view, the technological development of safe navigation, giving a chance to marine scientists and practitioners to obtain a comprehensive picture of the origins and evolution of modern navigation in the light of sea safety transit.

The Historical Route of Classical Navigation

1. The first steps up to 15th Century

It is commonly known that in the history of seamanship, the art of directing vessels upon the open sea have been traditionally taken place through the determination of its position and course using traditional practical methods, geometry, astronomy, or specific instruments. Great examples were the sailors who navigated in the Mediterranean, such as the Minoans of Crete. Minoans had been using several techniques to define their location; including maintain sight of land and understanding the tendencies of the winds as well as implementing the first forms of celestial navigation by knowing the position of particular stars. This constitutes an example of an early Western civilization that used celestial navigation, using the positions of particular stars. **[3]** In this context, written records of navigation using stars go back to Homer's Odyssey **[4]** or to the era of the voyage of the Greek navigator Pytheas of Massalia **[5]**, or even to Nearchos's famous voyage from India to Susa and the missions of the Greek navigator Eudoxus. **[6]**

Moreover, the Phoenicians and their successors, the Carthaginians, were especially skilled sailors. **[7]** On the other hand, the Arab civilization significantly contributed to navigation with its trade networks. That network would extent from the Atlantic Ocean through the Mediterranean Sea to the Indian Ocean and China Sea. **[8]** In addition, in China between 1040 and 1117, the magnetic compass was being developed and applied to navigation. **[9]** Nevertheless, the true mariner's compass started to be implemented in Europe no later than 1300. **[10]**

Also, nautical charts and relevant descriptive texts, known as sailing directions, have been in use since the 6th century BC, while nautical charts using stereographic and orthographic projections date back to the second century BC. **[11]** Nautical charts called **Portolan Charts** began to appear in Italy at the end of the 13th century. **[12]**

In general, in that period, the development of better navigational tools was a result of the advancement of commerce and trade.

2. 15th – 17th century

The commercial activities of Portugal between 15th and 16th century marked a milestone of significant progress in practical navigation. **[13]** Portuguese navigators made a distinct progress in oceanic navigation through the Atlantic, the Indian and the western Pacific oceans. **[14]** In the 15th and 16th centuries, the *Crown of Spain* followed in parallel the Portuguese global exploration. **[15]** Watching the Sun and stars, mariners began using special instruments to find latitude at sea. Trying to achieve that, they relied on the Sun and stars to tell time and determine their place on the open ocean. So, they managed to use angle-measuring instruments, which had become increasingly accurate by the end of the 1400s. **[16]**

Some of the early instruments for determining latitude were the cross-staff, the astrolabe, and the quadrant (see Figures 1,2,3 respectively). Moreover, the compass, the cross-staff or the astrolabe as well as rudimentary nautical charts were at the disposal of a navigator at the time of Christopher Columbus. These resources improved the ability of a navigator at sea to make an assessment upon his latitude. **[17].**

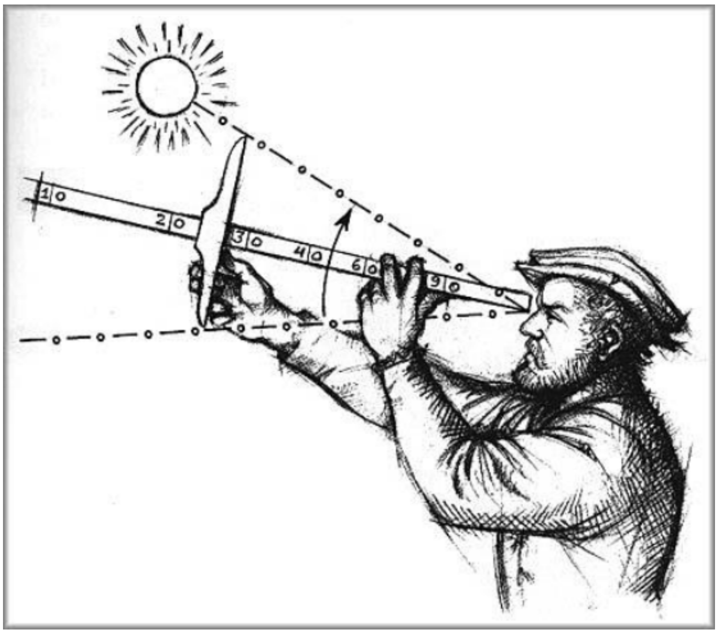

Figure 1: *The cross-staff (14th century) was an ancient precursor to the marine sextant*

Source: Canadian Museum of History, available at http://www.historymuseum.ca/cmc/exhibitions/hist/, (accessed: 01 June 2017)

Figure 2: *An astrolabe made in Paris (1400)*
Source: https://en.wikipedia.org/wiki/Astrolabe, (accessed: 20 May 2017)

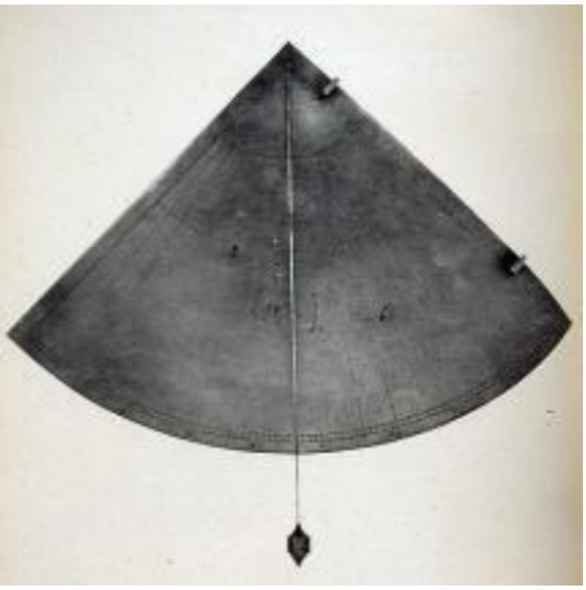

Figure 3: *A Seaman's Quadrant (1400)*
Source: Penobscot Marine Museum, available at http://www.penobscotmarinemuseum.org, (accessed: 20 May 2017)

Simple navigation methods and instruments served European navigators for centuries. Starting at a known position, the navigator could track the ship's compass heading and the ship's speed as well as the time spent on each heading and speed. Then, having determined those elements, the navigator could calculate the route and distance the ship had covered, plotting them on a sea chart. This method was called **dead reckoning**. In this process, one of the first navigational tools, the **mariner's compass -** an early form of the **magnetic compass** - was necessary. **[18]** A typical compass of the 16th century consisted of a large magnetized needle, connected to the underside of a circular card (compass card) on which the several directions were drawn (see Figure 4). **[19].**

Figure 4: *Dry Card Box Compass (16th century)*
Source: Penobscot Marine Museum, available at http://www.penobscotmarinemuseum.org, (accessed: 20 May 2017)

In 1577, a more developed technique was invented: the **chip log**, registered as patent in 1578. **[20]** Progressively, through the Middle Ages, continuous accumulation of navigational data, led to increased production of navigational info volumes, approached using mathematical tools and heading to a new scientific discipline: **"theoretical or scientific navigation"**. **[21]**

In the late 16th century, Gerardus Mercator made significant improvements to nautical charts (see Figure 5) with the first accurate representation of the spherical earth surface, namely the **Mercator Projection**. That was of great value to navigators because a compass bearing could be shown as a straight line, but the problem of determining longitude delayed the use of these charts for almost seventy years after they were introduced. In 1701, charts of magnetic variation were available, making the magnetic compass a valuable navigational tool. **[22]**

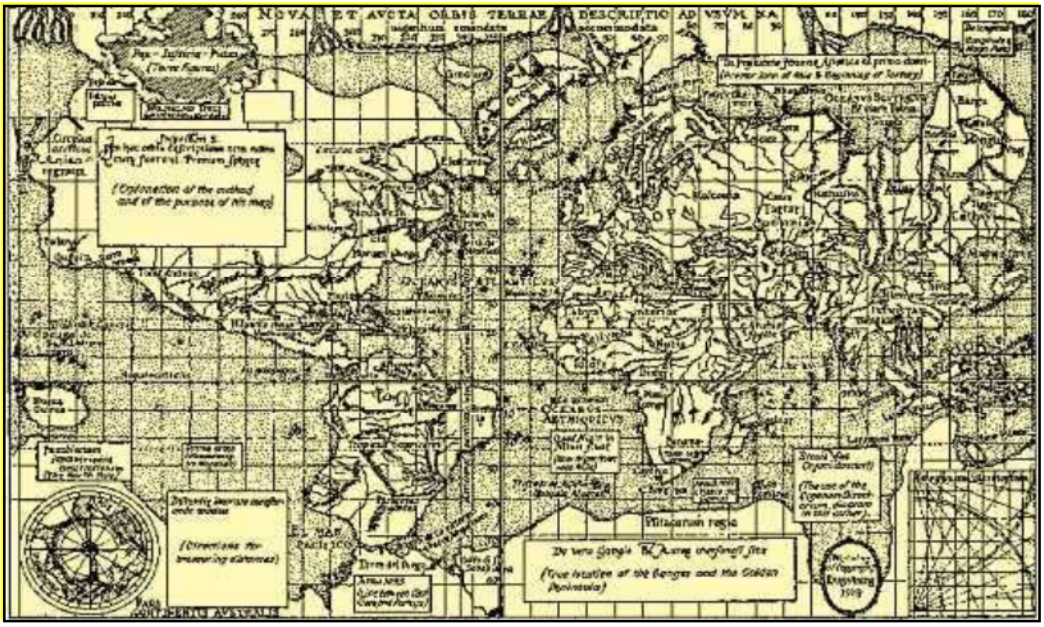

Figure 5: *An early years' (late 16th century) Mercator Projection map*
Source: https://www.britannica.com/science/world-map/images-videos, (accessed: 19 April 2017)

Another milestone in the history of classical navigation took place in 1637, when Richard Norwood, using a specially built astronomical sextant, measured the length of a nautical mile with chains. His result of 2,040 yards was very close to the modern International System of Units (SI) definition of 2,025.372 yards. **[23]** Furthermore, in 1671, the first of four volumes of *The English Pilot* appeared, covering mostly Europe, the Far East, and North America. A few years later, in 1675, the Royal Observatory was established at Greenwich, while in 1688 the **patent log** was invented, in which a vaned rotor was towed from the stern, and its revolutions were counted on a register. **[24]** One year later, in 1669 at Paris, the *Connaissance des temps*, the first national almanac was founded. **[25]**

3. 18th – 19th Century: Dealing with accuracy and safety concerns and the problem of determining longitude

18th century constituted a revolutionary era within navigation history. Around 1730, the **octant** (see Figure 6) was independently invented in England and the US. **[26]** In addition, in that century the **sextant** was invented (see Figure 7). This instrument replaced the Davis quadrant and the octant as the main instrument for navigation. The sextant provided mariners with a more accurate means of determining the angle between the horizon and the Sun, moon, or stars to calculate latitude, but it also helped for the lunar distance method to be applied. With the latter, navigators could find their longitude more accurately. **[27]**

Figure 6: *An Octant about 1730*

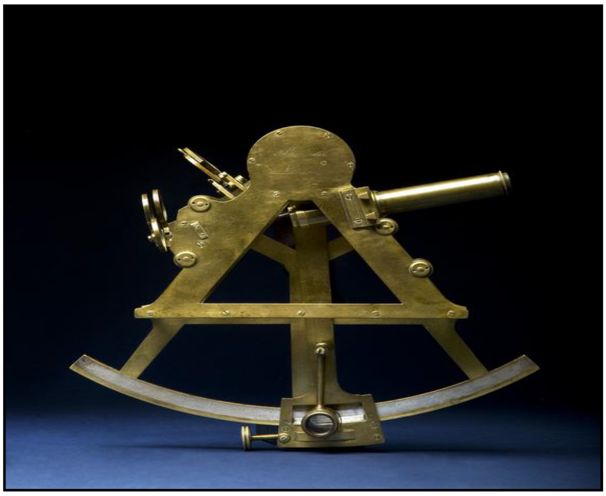

Figure 7: *A Sextant of 18th century*

Source: Smithsonian National Air and Space Museum, *Time and Navigation*, available at https://timeandnavigation.si.edu/multimedia-asset/sextant, (accessed: 15 March 2017)

In 1700, Europe's mariners and chart makers knew only about half the Earth's surface. On the open sea, sailors relied on dead reckoning, making estimations of a new position based on knowing a ship's last position, direction and speed. This method, however, over long distances, it was subject to ever-increasing errors. Finding latitude became easier with the invention of angle-finding instruments as mentioned above, but finding longitude remained difficult until a marine-type clock was perfected. The wreck of the *Arniston* proved the importance of measuring time with precision, thus finding longitude - especially in confined waters - leading gradually to the establishment of a maritime chronometer aboard every ship. **[28]**

In further detail, European governments offered big prizes to solve the longitude problem, because at the time no clock could keep better time than within about 15 minutes a day. In pursuit of a seaworthy clock, after the conception of a Galileo's idea, Christiaan Huygens, a mathematician from the Netherlands, patented the first working pendulum clock in 1656 (see figure 8) and later devised a watch regulator called a balance spring. **[29]** But several sea trials demonstrated to Huygens that the pendulum clock would never work accurately on a heaving ship's deck. **[30]** In 1714, Britain's Parliament, in the quest of solving the problem of finding longitude at sea, passed the *Longitude Act*, offering a huge price to the person who could have accomplished that. **[31]**

Under this motive, John Harrison, an English carpenter, in 1735, completed a clock based on a pair of counter-oscillating weighted beams connected by springs. The motion of its clock was not influenced by gravity or the motion of the ship. Gradually, he managed to solve precision issues that had been arisen until he perfected his work in 1761. In 1767, the Board of Longitude published his work under the title '*The Principles of Mr. Harrison's time-keeper*'. **[32]**

Marine chronometer (see figure 9) production was almost totally established in the late 18th century, and finally, a fairly accurate determination of longitude was accomplished. **[33]** Its modus operandi, in order to find longitude at sea, was rather simple: A chronometer was set to the time of a location of known longitude, i.e. Greenwich, England. Because one hour of difference in time equals 15 degrees difference in longitude, the difference in time between the chronometer and local time would bring in local longitude. **[34]**

Figure 8: *Dutch Table Clock with Pendulum about 1656* **[35]**

Source: Smithsonian National Air and Space Museum, *Time and Navigation*, available at https://timeandnavigation.si.edu/navigating-at-sea, (accessed: 15 March 2017)

Figure 9: *Chronometer movement, made by John Roger Arnold about 1825* **[36]**

Source: Smithsonian National Air and Space Museum, *Time and Navigation*, available at https://timeandnavigation.si.edu/navigating-at-sea, (accessed: 15 March 2017)

With the sextant for determining latitude and the chronometer for determining longitude, sailors by the 1800s were capable of navigating the high seas with better precision. M*oreover, nautical editions came up, mainly by Great Britain and the USA, such as* the annual *Nautical Almanac,* which was inaugurated in 1766 and t*he New American Practical Navigator, which* has served American sailors since 1802. **[37]** The latter, known as *Bowditch's Navigation* for its first writer, Nathaniel Bowditch, it still remains a useful handbook and essential navigation guide for astronomical tables, meteorological information as well as navigational instructions and methods(see Figure 10).

Furthermore, the celestial line of position concept came up in 1837 **[38]**, while in the 19th century the modern intercept method started to be applied. With this method the navigator can calculate the body height and azimuth for a convenient trial position and then to compare them with the observed height, finding at the end the difference in arc minutes. This difference is the nautical mile "*intercept*" distance, which is needed by the position line so that the latter can be shifted toward or away from the direction of the body's subpoint. Two other methods of reducing sights are the longitude by chronometer and the ex-meridian method. **[39].**

Better mapping and charting was one more issue of safety concern. On that purpose, the United States dispatched an ambitious mission to uncharted oceans under the command of Lt Charles Wilkes. **[40]** Wilkes and his crew made the most of the accuracy of their navigational instruments. Their observations resulted in some of the most accurate charts and maps of the time. **[41]** In addition, in 1884, it was decided by international agreement, that the meridian of Greenwich-England would be the **Prime Meridian** (0°). **[42]** Later on, the radio receiver would provide a continuously updated time signal from this Meridian. **[43].**

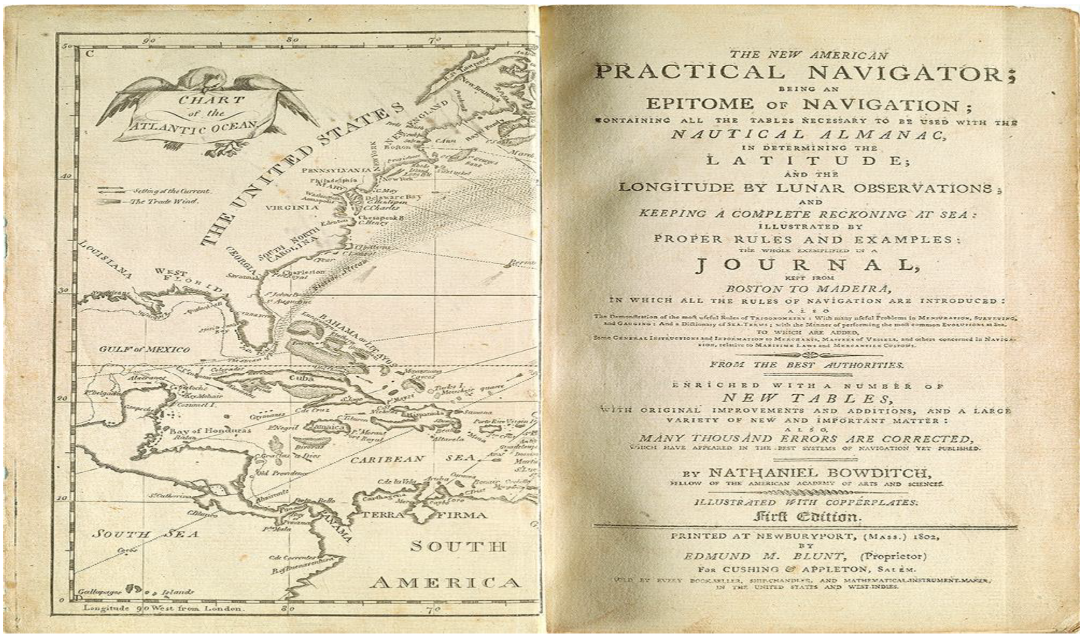

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Figure 10: *The New American Practical Navigator (1802)*

Source: Smithsonian National Air and Space Museum, *Time and Navigation*, available at https://timeandnavigation.si.edu/navigating-at-sea, (accessed: 15 March 2017)

Heading for the future:
The recent history of electronic navigation

4. 20th Century: Using radio waves and gyroscopic compasses on ships and establishing radio, radar and satellite navigation

The 20th century had probably witnessed the greatest advances ever in navigation tools. The impetus for these developments was no longer trade and exploration, but for use in military operations. However, many of these instruments and technologies have been adapted for civilian purpose use.

It was in 1891 that radios in the form of wireless telegraphs made their first appearance on ships at sea. **[44]** By 1904 time signals were being sent to ships to allow navigators to check their chronometers. The U.S. Navy Hydrographic Office was transmitting navigational warnings to vessels at sea by 1907. **[45]** Among the later developments one might mention the placing of lighthouses and buoys close to shore to clarify ambiguous features, highlight hazards and point out safe navigation channels for ships. At the same time, Elmer Sperry introduced the first **gyroscopic compass (or gyrocompass)** which points the true north rather than the magnetic north, being unaffected by variation or deviation. The significant advantage of gyrocompasses over magnetic compasses is that they find true north as determined by Earth's rotation, which is different from, and navigationally more useful than, *magnetic* north. **[46]**

1921 saw the installation of the first **radio beacon**. **[47]** The British physicist Robert Watson-Watt produced the first practical **radar** (RAdio Detection And Ranging) system in 1935, while in 1940 Alfred L. Loomis conceived the idea for an electronic hyperbolic air navigation system which was later developed into LORAN (Long Range Navigation System). **[48]**

After WWII, it was the time for satellite navigation to be boosted, in the context of the Cold War antagonism between the US and Soviet Union. Launching *Sputnik, the* world's first artificial satellite by the Soviets in 1957 as well as placing **TRANSIT** satellite navigation system in polar orbit by the Americans in 1960, constitute the first milestones of that huge progress of navigation. **[49]**

GPS (Global Positioning System), initiated in 1973, operated and maintained by the U.S. Department of Defense until nowadays. **[50]** Similarly, Russian **GLONASS** system began to be operational in 1982. The European Space Agency expected to have its **Galileo** system with 30 satellites in place when fully operational; however, there is some extra work to be done to reach full operational ability. **[51]**

Further down, we are going to examine in more depth the development of radio and satellite navigation.

a. Development of Radio Navigation

The first application of electronics to navigation was in 1865, which involved sending telegraphic time signals to check chronometer error. Later on, in 1904 radio time signals were transmitted for the chronometer. Radio broadcast, providing navigational warnings, begun in 1907 by the U.S. Navy Hydrographic Office, something that helped increase the safety of navigation at sea. **[52]**

The first system of radio navigation was **the Radio Direction Finder** (RDF). By tuning in a radio station and the use of a directional antenna, the direction to the broadcasting antenna could be determined. A second measurement using another station was taken after that, and, finally, by the use of triangulation, the two directions could be plotted on a map where their intersection defined the position of the navigator. **[53]** The first radio beacon was installed in 1921. Early 20th century led to the U.S. Navy's development of the first echo sounder in 1922.

Following the development of radio beacons, various **hyperbolic systems** have been developed, being the ancestors of satellite navigation. These systems were introduced during WWII and remained the main long-range advanced navigation systems until GPS 'replaced' them, or better, supplemented them, in the 1990s. Hyperbolic navigation systems are in fact a modified form of transponders. Instead of producing a single distance or angle they indicate a location along any number of hyperbolic lines in space. Two such measurements produce a fix, indicating the position of the vessel. The parallel use of those systems along with certain navigational charts finally eliminated the need for manual triangulation. **[54]** The first hyperbolic system to be developed was the British **Gee** system. **[55]**

Decca Navigator was another British system from the same era was (see Figures 11,12). Decca differed from Gee. Its signals were not transmitted pulses which were delayed in time, as in the case of Gee, but continuous signals which were delayed in phase. Time difference information returned by the phase comparison of the two signals returned. This was far easier to display than in the case of Gee. **[56]**

In their turn, based on the same principles, the US directed their effort to a much longer-range system which used lower frequencies. That system was named **LORAN** (LOng-range Aid to Navigation) and it allowed greater coverage across the Atlantic Ocean. The disadvantage was that accuracy was greatly reduced compared to the high-frequency systems. LORAN used pulsed radio signals transmitted from a master and a slave station. These signals were received onboard and recorded as waves on the display unit of a cathode-ray tube. The distance between the receiving waves corresponded to the time-difference between the arrivals of the signals from the two aforementioned stations and it was represented by a curve (hyperbola). In order to produce a position (fix) that process needed to be performed by another set of transmitting stations. The position of the vessel was situated at the intersection of the two produced curves (Loran Lines of Position). The accuracy of LORAN system varied between a few hundred meters and a few kilometers. **[57]**

Figure 11: *Decca Receiver (50s-60s)*

Figure 12: *Decca Receiver (70s-80s)*

Source: Pallikaris A., Katsoulis G., Historical Evolution and Prospects of Electronic Navigation (in Greek), Nausivios Chora, Volume 2, Hellenic Naval Academy, Piraeus, 2008, ISSN: 1791-4469

Figure 13: *Loran-A receiver (50s-60s)*

Figure 14: *Loran-C receiver (80s-90s)*

Source: Pallikaris A., Katsoulis G., Historical Evolution and Prospects of Electronic Navigation (in Greek), Nausivios Chora, Volume 2, Hellenic Naval Academy, Piraeus, 2008, ISSN: 1791-4469

In this context, Loran A (see Figure 13) was developed as a long-range marine navigation system. This was replaced by the more accurate Loran C system **[58]**, deployed throughout much of the world. LORAN-C (see Figure 14) was fairly complex to use, requiring a room of equipment to pull out the different signals. LORAN-C was the most popular navigation system in use through the 1980s and 90s. Moreover, various short range and regional hyperbolic systems have been developed by private industry for hydrographic surveying, offshore facilities positioning, and general navigation.

Similar to LORAN hyperbolic systems followed by both the US and the USSR, namely the US global-wide VLF/Omega Navigation System (see Figure 15), and the Soviet Alpha system. The operating concept of these relied on the determination of pulse timing not by comparison of two signals, but by comparison of a single signal with a local atomic clock. Nevertheless, Omega system was shut down in 1997 when the US military had already turned towards GPS. **[59].**

Figure 15: *Omega Navigation Satellite System (70s-80s)*
Source: Pallikaris A., Katsoulis G., Historical Evolution and Prospects of Electronic Navigation (in Greek), Nausivios Chora, Volume 2, Hellenic Naval Academy, Piraeus, 2008, ISSN: 1791-4469

b. Development of Radar Navigation and Radio Transponders:

In 1935 the British had already begun work on **radar**. **[60]** In 1937 the US introduced the first sea-going radar. However, the foundation of the principle of the multicavity magnetron belongs to the British, developed by J. T. Randall and H. A. H. Boot at the University of Birmingham in 1939. In 1945, and after a very successful use by the British and Americans during WWII, radar became available for commercial use. The basic principle of radar function is simple; transmitter periodically sends out a short pulse of a radio signal using a broadcast antenna. When the signal reflects off a target, a part of that signal is reflected back in the direction of the transmitting station. The received signal has to be powerfully amplified in order to be used since it constitutes is a small fraction of the broadcast power. After amplification, the signal may be displayed on the operator’s video-display unit. **[61]**

After years of evolution, modern marine and aviation radar systems can provide nowadays very useful navigation information, starting from the most essential; taking only distances and angular bearings to charted objects and use these to establish arcs of position and lines of position on a chart. Moreover, using Parallel indexing technique, safe navigation and hazard’s avoidance can be enhanced. **[62]** From the time radar was first introduced to our time, the way in which radar picture is presented has changed considerably since we’ve moved from cathode ray tube screens to raster-scan displays. **[63]**

Further evolving the navigation radar, the **automatic radar plotting aid (ARPA)** capability has come up (see Figure 16) thanks to the availability of low-cost microprocessors and the development of advanced computer technology during the 1970s and 1980s. **[64]** ARPAs are computer assisted radar data processing systems. These systems generate predictive vectors and other ship movement information, creating tracks using radar contacts. The system has the capability to calculate the tracked object's course, speed and closest point of approach (CPA). In other words it can identify a potential risk of collision with another ship or landmass. **[65]** Consequently, the main advantages of ARPA are a reduction in the workload of the bridge team and more integrated and quicker information on selected targets.

Figure 16: *A typical shipboard radar system with ARPA Display of 20th-21st century*
Source: https://en.wikipedia.org/wiki/Automatic_radar_plotting_aid, (accessed: 12 May 2017)

The International Maritime Organization (IMO) has instituted certain standards amending the International Convention for the Safety of Life at Sea (SOLAS) requirements regarding the use of suitable Automated Radar Plotting Aids.

The **Radio Transponder** appeared soon after the introduction of radar. Radio Transponders are a combination of receiver and transmitter devices whose operation is fully automated. Upon reception of a particular signal, normally a pulse on a particular frequency, the transponder transmits a pulse in response, with a certain short time delay. **[66]** The use of radio transponders is essential in Global Maritime Distress and Safety System (GMDSS). IMO has set out the institutional framework of the GMDSS to provide the communication support needed to implement search and rescue plans. This system, which all almost maritime nations-states have been implementing since its institution, is based on a combination of satellite and terrestrial radio services. GMDSS has changed the modus operandi of international distress communications, from being primarily ship-to-ship based to ship-to-shore (Rescue Coordination Center) based. **[67]**

The main types of radio transponder equipment used in GMDSS **[68]** have as follows:

(i) Emergency Position-Indicating Radio Beacons (EPIRBs): These automatic-activating devices (see Figure 17) are in use under the function of *Cospas-Sarsat*, an international satellite-based search and rescue system, established by Canada, France, the US, and Russia. EPIRBs, now required on SOLAS ships, commercial fishing vessels, and all passenger ships. **[69]**

(ii) Search and Rescue Transponders (SARTs): The GMDSS installation on ships includes one (two on vessels over 500 GT) Search and Rescue Locating device(s) called Search and Rescue Radar Transponders (SART) (see Figure 18) which are used to locate survival craft or distressed vessels. This is taking place by creating a series of twelve dots on a rescuing ship's radar display. The detection range between these devices and ships is dependent upon the height of the ship's radar mast and the height of the Search and Rescue Locating device. It is normally about 15 km (8 nautical miles). Once detected by radar, SARTs will produce a visual and aural indication to the persons in distress. **[70]**

Figure 17: *EPIRB Device*

Source: https://www.egmdss.com/gmdss-courses/mod/resource/view.php?id=885, (accessed: 15 June 2017)

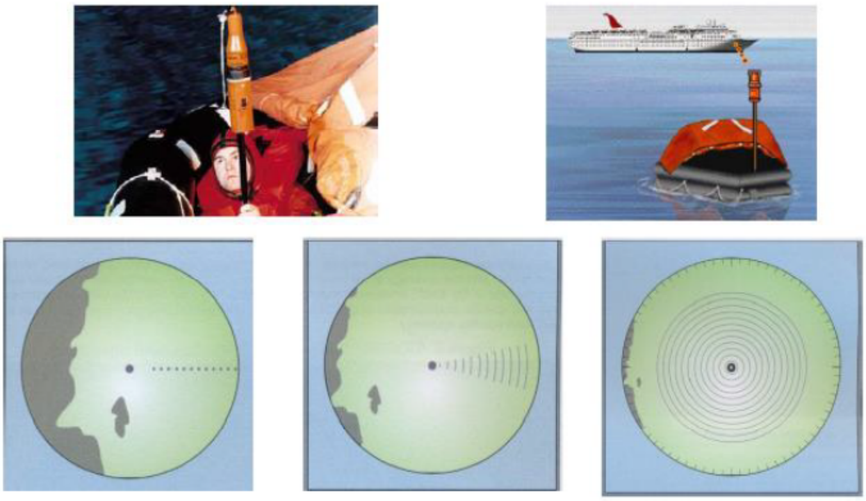


Figure 18: *SART Device and Radar Video Image*

Source: Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2^{nd} edition, Eugenides Foundation, Athens, 2016

c. Development of Satellite Navigation

A **satellite navigation** or **satnav** system is a system of orbiting satellites which provide autonomous geo-spatial positioning with global coverage. It allows electronic related receivers to determine their position (longitude, latitude, and altitude/elevation) very accurately (within a few meters) using time signals transmitted along a line of sight by satellites' radio waves. This is done by the capability given to the receiver to calculate the current local time to high precision, allowing time synchronization. A satellite navigation system with global coverage may be termed a **“Global Navigation Satellite System (GNSS)”**. **[71]**

Plans to navigate from space were inspired by the possibility of traveling in space. In the quest of various innovators to see whether radio transmissions from orbiting satellites could be used to determine positions on Earth, they finally ended up with the conclusion that time from precise satellite-fitted clocks, transmitted by radio signals could, in fact, determine position. The US military, after the combination and integration of several systems into one, created the Global Positioning System (GPS). Manufactured consecutively by Rockwell International (1974-1986) and by Lockheed Martin (1990s-thereafter), more than 30 GPS satellites were operational after 2010. **[72]** Its early predecessors, as mentioned before, were the ground based DECCA, LORAN, GEE and Omega radio navigation systems.

Nevertheless, the direct ancestor of satellite navigation had been the Inertial Navigation. An **Inertial Navigation System** (INS) uses motion and rotation sensors along with a computer to figure out the position, direction, and speed of a vehicle’s movement either on air, sea or land without using the stars or other outside visual references. **[73]**

However, the concept for the first space-based navigation system was born in 1957 in the USA, and by 1964, the US Navy was using radio signals from its own satellites under **Transit** system (see Figure 19) to navigate submarines and surface vessels. In that sense, Transit satellites are considered to be the first working system of satellite navigation. Nevertheless, Transit satellites were not designed to provide accurate time. But they did carry ultra-precise quartz oscillators to control their radio frequencies. **[74]**

Figure 19: *TRANSIT System’s Components (1964)*
Source: Smithsonian National Air and Space Museum, *Time and Navigation*, available at https://timeandnavigation.si.edu/satellite-navigation, (accessed: 15 March 2017)

Transit's operation was based on the Doppler Effect. The satellites traveled on known paths and broadcast their signals on known frequencies. The received frequency was slightly different than the broadcast frequency. This was happening because of the relative movement of the satellite with respect to the receiver. By tracking this frequency shift over a short time interval, the receiver could determine its location to one side or the other of the satellite. Several such measurements combined with the knowledge of the satellite's orbit could fix a particular position. **[75]**

However, during the Cold War, U.S. defense planners were in the quest of a global navigation system that would be more accurate than the Navy’s Transit system. In this context, the Naval Research Laboratory in the 1970s launched the TIMATION Program, inventing new navigation techniques based on the function of atomic clocks in space. Such a technique was implemented in 1977 under the conception of “Navigation Technology Satellite 2 (NTS-2)”. Two cesium atomic clocks on board of those pioneer satellites linked satellite navigation to precise timing, thus making a breakthrough in navigation methods. Progressively, in 1973, the Defense Department combined its competing satellite navigation systems, coming finally up in 1974 with a program under the Air Force, which was called the **NAVSTAR Global Positioning System, or GPS**. **[76]** GPS introduced synchronized time from space, accomplished by onboard atomic clocks. As designs evolved, positioning and navigation accuracy gradually improved to a higher degree. GPS works in general as follows:

(i) Firstly, tracking stations use radio signals to determine orbits of GPS satellites and in their turn command centers transmit orbital data, time corrections, and location of other satellites in the GPS constellation.

(ii) Then, the GPS satellites simultaneously transmit synchronized time and orbital data to Earth and relative GPS receivers determine the location using orbital data and arrival time differences of the received signals from at least four satellites. **[77]**

Position accuracy depends on the receiver. Modern civilian GPS receivers are accurate to about 10 to 20 meters (33 to 66 feet) while for military and other more specific applications the accuracy may be higher. **[78]**

Along with the US, different nations have developed and deployed independent navigation capabilities using GNSS systems. These capabilities have been achieved by a satellite constellation of 20–30 Medium Earth Orbit (MEO) satellites spread between several orbital planes. Examples of GNSS receivers and its subsystems are depicted in Figures 20 and 21.

The basic position determination principle using a contemporary Global Navigation Satellite (GNSS) system is very simple (see Figure 22): If both the distances between a satellite receiver of a GNSS system and three satellites at least and the exact position of those satellites are known, then the exact location of the receiver is determined at the intersection of those spherical surfaces that have as centers the aforementioned satellite positions and their radius are equal to the measured satellite-receiver distances. However, in practice, the implementation of the above simple general principle is simplified through a series of complex processes and functions by measuring the distances between the receiver distances and more than three satellites. **[79]**

Figure 20: *Modern GNSS receiver*

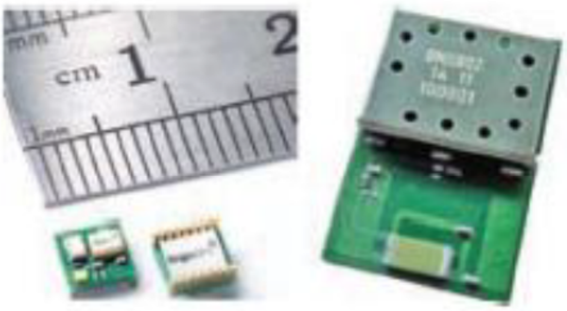
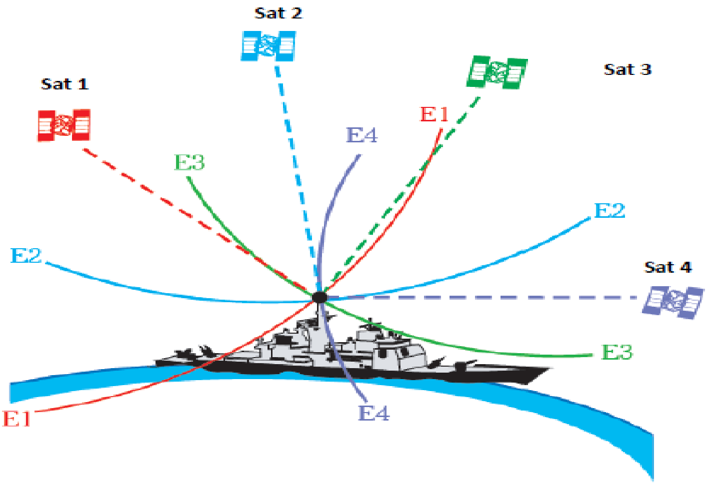


Figure 21: *GNSS receivers in form of a microcircuit, compatible with GPS, GLONASS, Beidu and other systems*

Source: Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2nd edition, Eugenides Foundation, Athens, 2016

Figure 22: *The basic principle of determining position with the use of global satellite navigation systems: ["Ship's position lies at the intersection of the spherical surfaces E1, E2, E3 and E4, which have their centers at the points where the satellites 1, 2, 3 and 4 are located and as radii the relevant distances measured by them"]*

Source: Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2^{nd} edition, Eugenides Foundation, Athens, 2016



The most important of those processes are summarized as follows:

i) The location of the satellite receiver on the Earth's surface (i.e. ship's position), or near the Earth's surface (i.e. aircraft position) is determined in relation to the positions of the satellites of the GNSS system used (i.e. GPS, Glonass, Galileo, etc.).

ii) In the GNSS satellite navigation systems, the positions of the satellites are not constant, but they change at any given time due to their movement to elliptical trajectories. However, the precise positions of the satellites at any time, and therefore at the time of determining the location of the satellite receiver, can be precisely determined according to Kepler's Laws. **[80]**

iii) Each satellite of a GNSS system (GPS, Galileo, Glonass, etc.) emits a complex pulsed encoded satellite signal, associated with its transmission time. The satellite signals provide the receiver with all the information needed to determine the position, such as the exact positions of satellites (satellite newspapers), etc. **[81]**

iv) Receiver distances from the satellites result from measuring the propagation time of the satellite signals multiplied to the propagation velocity of the electromagnetic waves. Distances measured in this way contain some errors, so they are called "pseudo-distances". **[82]**

v) The errors of the measured pseudo-distances are mainly due to the fact that the timers of the satellite receivers are not as accurate as the satellite timers, as well as due to the change in the propagation velocity of the satellite signals in the ionosphere and the troposphere.

vi) Correction of the total pseudo-distances error requires simultaneous reception of signals from at least four satellites instead of the three normally required

vii) For calculating receiver distances from satellites, apart from the aforementioned basic method of measuring the propagation time of satellite signals, the phase comparison method, which provides much higher accuracy, is also used.

viii) The phase comparison method is mainly used in geodetic applications, such as the Real Time Kinematic Positioning (RTK) method. **[83]**

ix) For the precise determination of the location of the satellites, the GNSS systems have a ground monitoring and control unit, which consists of:

a) A network of terrestrial monitoring stations.

b) A main control station.

c) Ground stations for transmitting the elaborated elements of the main control station to the satellites for further retransmission to the satellite maritime receivers. **[84]**

x) In order to perform the calculations required to determine the location of the receiver, both the position of the satellite receiver and the positions of the satellites must be referred to a common geodetic reference system (geodetic datum system) such as the WGS-84 reference geodetic system used in the GPS system or the PZ-90 reference geodetic system used in the Glonass system. However, regardless of the geodetic reference system used to calculate the coordinates of the receiver's location, GNSS receivers can convert these coordinates into several geodetic reference systems (ED-50, Tokyo datum etc.), depending on the user's options. **[85]**

The most significant GNSS systems (either of global or regional cover) are: **[86]**

(i) **GPS [87]:** Operated by the U.S. Department of Defense in cooperation with the U.S. Department of Transportation and other civilian government agencies. It consists of up to 32 medium Earth orbit satellites in six different orbital planes (see Figure 23). Its satellites are positioned in precise orbits 18,000 kilometers above the Earth. They orbit once every 12 hours, transmitting synchronized time and orbital data to earth. **[88]** It is nowadays the world's most utilized satellite navigation system.

(ii) **GLONASS [89]:** GLObal NAvigation Satellite System or GLONASS) was initially developed by the Soviet Union during the Cold War. Now it is operated as a GNSS by Russia’s Federal Space Agency (see Figure 24). Having passed a period of disrepair after the end of Cold War, it has been again fully operational since 2011.

(iii) **Beidou [90]:** The Beidou Navigation Satellite System (BDS) has been planned and developed by the government of China with the aim to reach global coverage with about 35 satellites in 2020. (see Figure 25). China is in the process of upgrading the system under the name BeiDou-2 system, which is proposed to consist of 30 MEO satellites and five geostationary satellites.

(iv) **IRNSS [91]:** India has for the moment a satellite-based augmentation system, which is called “GPS Aided GEO Augmented Navigation (GAGAN)”. This system enhances the accuracy of GPS and GLONASS positions. However, the Indian Space Research Organisation (ISRO) began developing the Indian Regional Navigational Satellite System (IRNSS) in 2006 under the name **“NAVIC (NAVigation with Indian Constellation)** to provide positioning services around India. It is actually an autonomous regional satellite navigation system under the control of Indian government. It consists of a constellation of 7 navigational satellites, intended to provide an absolute position accuracy of fewer than 7 meters throughout and around India within a region extending approximately 1,500 km. The launch of satellites has started since 2013.

(v) **QZSS [92]:** The Quasi-Zenith Satellite System (QZSS), is a proposed three - satellite regional time transfer and enhancement for GPS system with the aim to cover Japan. The first satellite launched in September 2010.

(vi) **Galileo:** It is under constant development as a civilian-operated global system by a consortium of EU countries. Operations are coordinated by the European Commission and the European Space Agency, the latter agreed in March 2002 to introduce its own alternative to GPS. Galileo positioning system (see Figure 26) is expected to be compatible with the modernized GPS system, thus providing higher accuracy. **[93]** The complete 30-satellite Galileo system (24 operational and 6 active spares) is expected to be operational by 2020. It will have five basic services:

- Open access navigation
- Commercial navigation with an 1-cm precision (charged with fees)
- Open service for navigational safety
- Public regulated navigation (encrypted for use by government agencies)
- Global Search and rescue. **[94]**

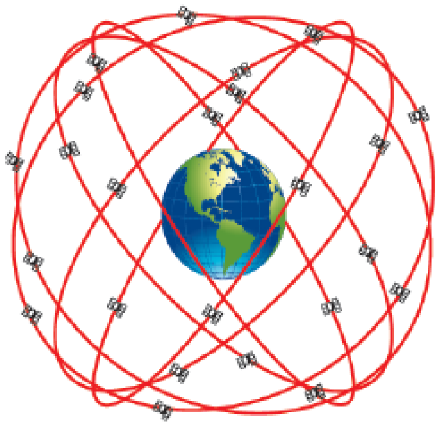


Figure 23: *GPS Constellation*

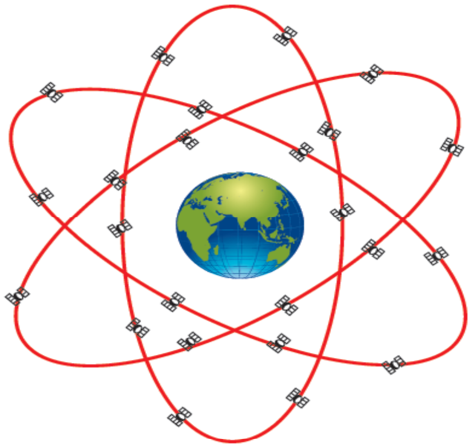


Figure 24: *GLONASS Constellation*

Source: Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2nd edition, Eugenides Foundation, Athens, 2016

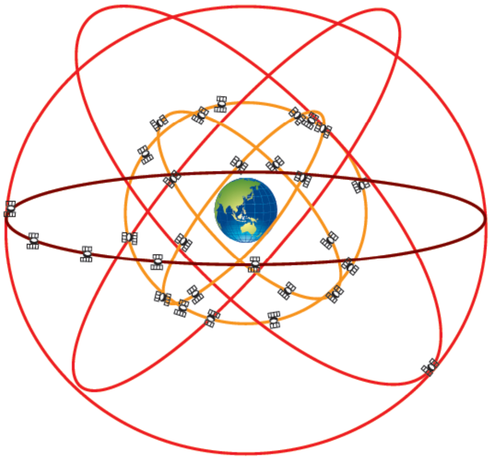


Figure 25: *BEIDU Constellation*

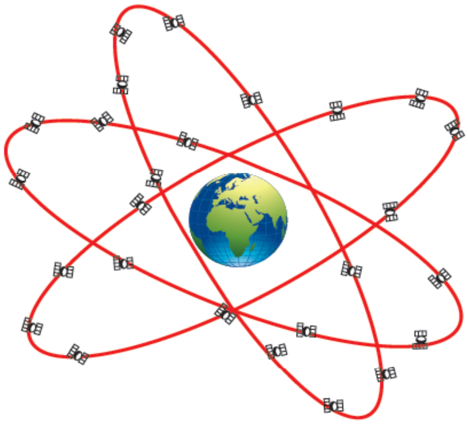


Figure 26: *GALILEO Constellation*

Source: Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2nd edition, Eugenides Foundation, Athens, 2016

The breakthrough and the way ahead

5. 21st Century: The development of modern electronic navigation

The beginning of 21st century witnessed a technological breakthrough as far it concerns digitalization, interconnectivity, integration and interoperability of electronic navigation equipment. That has happened for the sake of time-saving, better accuracy and direct and faster management of safety/security issues. In this spectrum, electronic chartering has been introduced and used widely, automatic tracking systems for vessel traffic services have been fitted on vessels as well as integrated bridge systems have reduced the workload of navigators while enhancing the safety of ships.

a. Electronic Charts and relevant Display Information Systems [95]

An **electronic navigational chart (ENC)** is an official database created by a national hydrographic office, in most cases for use with an Electronic Chart Display and Information System (ECDIS). An electronic chart (see Figure 27) has to conform to standards stated in the International Hydrographic Organization (IHO) relevant publications before it can be certified as and be used within ECDIS to meet the International Maritime Organization (IMO) performance standards for ECDIS. **[96]** IMO has adopted mandatory carriage of ECDIS and ENCs on new high-speed vessels since the 1st of July 2010 and progressively for other crafts from 2012 to 2018. There are certain types of electronic chart data, namely:

(i) **ENC charts:** These are vector charts that conform to the requirements for the chart databases for ECDIS. They are structured with standardized content and format, being issued for use with ECDIS. ENCs contain all the necessary information for safe navigation, as in the case of paper nautical charts. However, they may contain additional information, also necessary for safe navigation. **[97]**

(ii) **Raster charts:** Raster navigational charts (RNCs) are raster-type graphics maps, conformed to IHO specifications. They are produced by the conversion of paper charts to digital image by scanner. **[98]**

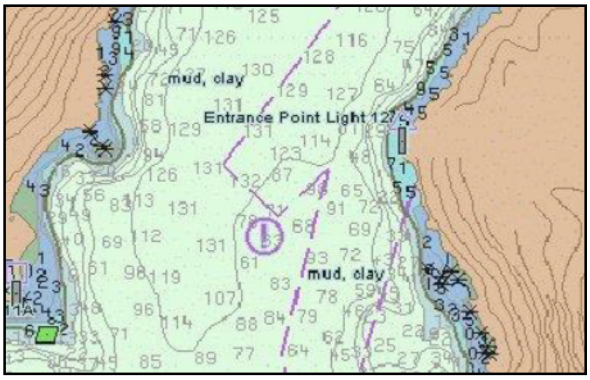


Figure 27*: Electronic Navigational Chart*
Source: https://en.wikipedia.org/wiki/Electronic, Navigational Chart, (accessed: 05 May 2017)

Figure 28: *A modern ECDIS Console*
Source: Sperry Marine, available at http://www.sperrymarine.com/visionmaster-ft-ecdis, (accessed: 05 May 2017)

An **electronic chart display and information system (ECDIS)** is a computer-based navigation information system. This type of electronic navigation systems are complying with IMO regulations, providing mariners the alternative of using electronic charts than paper nautical charts **[99].** ECDIS integrates a variety of real-time information, being an automated decision aid for continuously determining a vessel's position about land, charted objects, navigation aids and unseen hazards. **[100]** ECDIS (see Figure 28) provides continuous rather accurate position and navigational safety information. It can also generate audible and/or visual alarms when the vessel is in proximity to navigational hazards. The performance requirements for ECDIS are, as mentioned above, defined by IMO **[101]**. The consequent test standards have been developed by the International Electrotechnical Commission (IEC) **[102]**.

b. AIS Transponders [103]

Automatic Identification Systems (AIS) are designed to be able to provide information about the ship to other ships and coastal authorities automatically. **[104]** In this sense, AIS information supplements navigation radars, which continues along with visual navigation to be the primary method of collision avoidance at sea. The information provided by AIS equipment includes unique vessel's identification, position, course, and speed. It can be displayed on a screen or an ECDIS. Furthermore, AIS integrates a standardized VHF transceiver with a positioning system such as a GPS receiver as well as with other electronic navigation sensors. **[105]** The transmitted signals from AIS stations are received by AIS transceivers (see Figure 29) fitted on other ships or on land based systems, such as Vessel Traffic Services (VTS) systems of port authorities. Therefore, vessels fitted with AIS transceivers can be tracked by AIS base stations located either along coast lines or, when out of range of terrestrial networks (see Figure 30), through satellites. **[106]** The International Maritime Organization's International Convention for the Safety of Life at Sea (SOLAS) requires AIS to be fitted onboard international voyaging ships with gross tonnage (GT) of 300 or more as well as on all passenger ships regardless of size.

Figure 29: *An AIS-equipped system on board a ship, presenting the bearing and distanceof nearby vessels in a radar-like display format*

Source: https://el.wikipedia.org/wiki/media/File:Ais_dcu_bridge.jpg, (accessed: 10 June 2017)

The original purpose **[107]** of AIS was solely collision avoidance. Notwithstanding, many other applications have since developed, namely fishing fleet monitoring and control, vessel traffic services, search and rescue, maritime security aids to navigation etc. **[108]** Used for collision avoidance, the technology of AIS identifies every vessel individually, along with its specific position and movement. It thus enables a virtual picture to be formed in real time (see Figure 31) **[109]**.

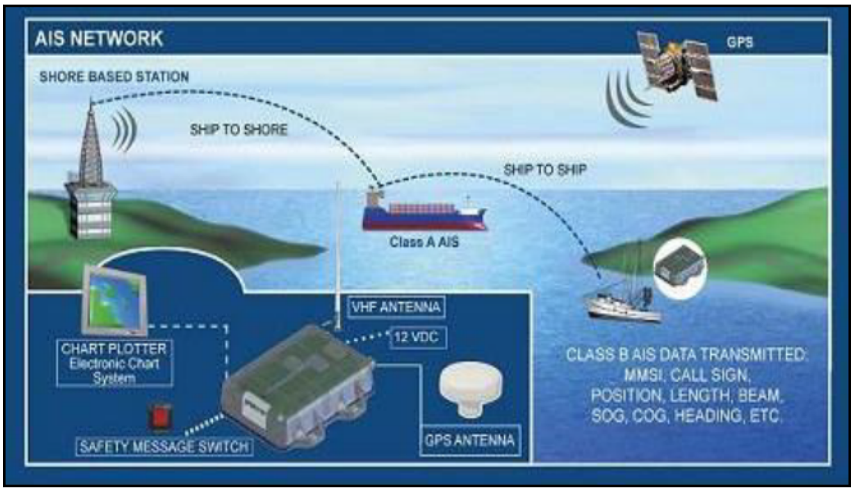


Figure 30: *The AIS network*
Source: Marine Electronics Journal, available at https://www.marineelectronicsjournal.com/content/, (accessed: 05 April 2017)

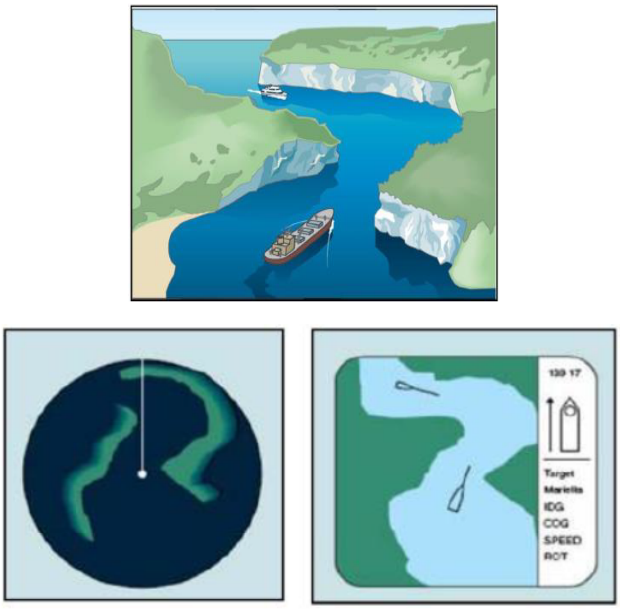


Figure 31: *The use of AIS in collision avoidance*
Source: Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2nd edition, Eugenides Foundation, Athens, 2016

c. Integrated Bridge Systems (IBS)

An **Integrated Bridge System (IBS)** is defined as "*a combination of systems which are interconnected in order to allow centralized access to sensor information or command/control from workstations, with the aim of increasing safe and efficient ship's management by suitably qualified personnel*" (see Figure 32). **[110]** It is notable that not all types of ships have the same type of IBS, the latter varying according to the design of the ship's bridge, the variety of the equipment's types used by the ship, and the general layout of the bridge's equipment. **[111]** IMO, in 1996, adopted performance standards for IBSs. **[112]** In case of failure of any navigation, engine, power distribution or other important subsystem, an integrated alarm system must provide a suitable warning to the officer on watch (OOW) of the potential danger. The following sub-systems are generally connected to an IBS: i) Autopilot ii) Radar iii) Gyro iv) Position fixing systems v) ECDIS vi) Power distribution system vii) Steering gear. An alarm system links all the systems above and transmits audio and visual signal in case of any emergency. However, there can be more systems connected to the IBS and to the alarm system. **[113]** Though IBS constitutes an excellent system for navigation, officers on watch should always pay proper attention to visual navigational watch keeping, since the latter provides arguably a much higher confidence level as well as reliability. **[114]**

Figure 32: *Image of a modern vessel's bridge equipped with IBS*
Source: Sperry Marine, available at http://www.sperrymarine.com/integrated-bridge-system, (accessed: 20 June 2017)

Conclusive remarks

Despite the constant evolution of technology, the basic principles and requirements of navigation have remained unchanged over time, summarized in avoiding grounding as well as preventing damage due to adverse weather conditions. The only changes that have been created over time are the modernization of the methods and the resources allocated to achieve these basic objectives. Characteristically, we can refer to the usual case of the methods of classical navigation, i.e. the use of a lantern of the lighthouse network, the repeater of the gyro compass for measuring true bearing, the traditional radar with analog monitor for measuring distance or even the traditional printed map and drawing instruments for depicting the position of the ship and subsequently evaluating the accuracy of that position. All of this process requires marine perception, experience and knowledge. The same exact procedure can be achieved nowadays with other navigational aids and tools, such as the GNSS system satellites (instead of a lighthouse network), the electronic navigation maps (instead of paper maps) and the ECDIS system (instead of drawing instruments).

The modernization of navigation methods and the development of advanced systems for automating traditional shipping have by no means transformed the role of the navigation watch officer in a simple plain operator to monitor and record the status of a fully automatic system. On the contrary, the use of automated methods requires a high degree of training, readiness and alertness for the selection, evaluation and appropriate use of both integrated navigation systems (INS) and integrated bridge systems (IBS) **[115]**. To this purpose, the dynamic development of maritime systems and their components is implemented by international standards in order to ensure the required accuracy and interoperability.

The main developments in electronic navigation, as assessed and/or proposed by various working groups, the International Maritime Organization **[116]** and other relevant institutions such as the International Hydrographic Organization (IHO) **[117]** and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) **[118]**, are as follows:

i. Improvement of the existing geographic coverage of ENCs towards full global coverage.

ii. Review the technical specifications of ENCs.

iii. Improvements to the ECDIS system, like:
  - Possibility of three-dimensional imaging of the coast and the seabed.
  - Enrichment of the system database by issuing navigational editions (i.e. pilots, radio signals, etc.) in digital form.

iv. Improvement of the interoperability and mutual support of the satellite subsystems of GNSS (GPS, GLONASS, GALILEO, etc.).

v. Completion of the GNSS system with terrestrial electronic positioning systems (new generation of hyperbolic navigation systems) as well as with inertial navigation systems.

vi. Improvement of the existing network of ground-based navigation aids - including the classic lighthouses network - with sophisticated interactive aids.

vii. Complete interface of integrated navigation systems (INS) **[119]** and integrated bridge systems (IBS) **[120]** with sophisticated telecommunications systems for providing additional information about monitoring and controlling maritime traffic, search and rescue, marine environmental protection, long-range identification and tracking systems (LIRT) and others.

Concluding, it is more than obvious that the evolution of both safe navigation and maritime/shipping operations and related technology go hand in hand, heading towards a brighter future where automatization, integration and interoperability will in high degree be determining accuracy, safety, security and effectiveness. To this end, standardization and positive control by international and national institutions /authorities should be welcomed provided that we all want to effectively combine profit and performance with safety, protection of human life and environment and respect of the rules of law.

Nevertheless, as it was derived by the abovementioned analysis, navigational safety has much to do with positioning accuracy, In this respect, resolving the “time” issue at its highest precision stands even today a cornerstone in every facet of modern electronic and satellite navigation. Hence, the whole scientific community will never stop its efforts to achieve “absolute” perfection in determining exact time with more simplified processes and lower cost in order to meet the demands of the end-user, for both civilian and military purposes.

Bibliographic References

1. See Edward W. Anderson, ‘Navigation Technology,' *Encyclopedia Britannica*, available at https://www.britannica.com, (accessed: 12 Oct 16).

2. See US National Imagery and Mapping Agency, *The American Practical Navigator: An Epitome of Navigation* (originally by Nathaniel Bowditch, LL.D), 1995 Edition, Maryland, USA, 1995.

3. See The Mariners' Museum, *The Age of Exploration,* Newport News, Virginia, available at http://www.mariner.org/age/index.html, (accessed: 1 Nov 16).

4. See Toghill, Jeff E. *Celestial Navigation, New* York, W. W. Norton & Co., 1988.
5. Pytheas, competent astronomer and geographer, sailed from Greece through the Strait of Gibraltar to Western Europe and the British Isles. He is the first known person to describe the Midnight Sun and the polar ice as well as the idea of distant “Thule”. *See* Bilic, Tomislav, ‘The Myth of Alpheus and Arethusa and Open-Sea Voyages on the Mediterranean--Stellar Navigation in Antiquity’, *International Journal of Nautical Archaeology,* 38 (1), March 2009, pp. 116–132.
6. See *The Geography of Strabo*, Book II, Ch3, in Loeb Classical Library Ed., 1917.
7. See Donald Harden, *The Phoenicians,* Penguin Books, Harmondsworth, p. 168. See also Taylor, E. G. R., *The haven-finding art; A History of Navigation from Odysseus to Captain Cook,* New York, American Elsevier Publishing Company, 1971. See also John M. Hobson, *The Eastern Origins of Western Civilisation,* Cambridge University Press, 2004, p.141.
8. See Subhi Y. Labib (1969), ‘Capitalism in Medieval Islam’, *The Journal of Economic History,* 29 (1), p. 79-96.
9. See Li Shu-Hua, ‘Origine de la Boussol, Aimant et Boussole', *Isis*, Vol. 45, No. 2., Jul 1954, p.181.
10. This compass depends on the use of a piloting needle in a dry box. See Frederic C. Lane, ‘The Economic Meaning of the Invention of the Compass’, *The American Historical Review*, Vol. 68, No. 3, Apr 1963, p.615ff.
11. See US National Imagery and Mapping Agency, *The American Practical Navigator: An Epitome of Navigation*, op.cit.
12. See Rosenbach Company, *The Sea: Books and Manuscripts on the Art of Navigation, Geography, Naval History, Shipbuilding, Voyages, Shipwrecks, and Mathematics, Including Atlases and Maps,* Storrs-Mansfield, CT: Maurizio Martino Publishers, 2003.
13. Those expeditions carried out by Henry the Navigator. See Kenneth Maxwell, *Naked Tropics: essays on empire and other rogues*, Routledge, 2003, p. 16ff.
14. Ibid.
15. Ibid.
16. See *Navigating at Sea*, Smithsonian Institute, available at https://timeandnavigation.si.edu, USA, (accessed: 20 Oct 2016).
17. The quadrant, the first device used to find latitude, was a quarter-circle of wood, marked in degrees, with a plumb line and a sight along one edge. It was first used at sea around 1460. Another early latitude-measuring device was the astrolabe. It dates back to ancient Greece when it was used by astronomers to help tell time. The astrolabe is a disc with degrees and a movable arm with sights. It was first used at sea about 1481. See William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973.
18. Early navigators had the impression that the mariner's compass was often inaccurate because they did not realize the concept of magnetic variation. Magnetic variation is the angle between true north (geographic) and magnetic north. See Rosenbach Company, *The Sea: Books and Manuscripts on the Art of Navigation, Geography, Naval History, Shipbuilding, Voyages, Shipwrecks, and Mathematics, Including Atlases and Maps,* Storrs-Mansfield, Maurizio Martino Publishers, 2003.
19. See Olivia Isil, edited and expanded by Lebame Houston and Wynne Dough available at https://www.nps.gov/fora/learn/education/navigation-and-related-instruments-in-16th-century-england.htm, (accessed: 1Oct 16).
20. It was essentially an early-stage speedometer, in which a thin line was knotted at regular intervals and weighted to drag in the water. This device tossed overboard over the stern and as the navigator counted up the knots that were let out during a specific period, he could determine the speed of the vessel. See http://www.penobscotmarinemuseum.org/pbho-1/history-of-navigation/ navigation-american-explorers-15th-17th-centuries, (accessed: 1 Nov 16).
21. See William Edward, op.cit.
22. In 1569 the Flemish cartographer Gerardus Mercator published a world map that he had composed using a “projection suitable for navigation,”. Mercator, he did not disclose the details that map. In 1599 the English mathematician Edward Wright supplied a logical explanation of Mercator’s projection and

provided tables by which the distorted distances of the Mercator's chart could be corrected. On a Mercator chart, the meridians of longitude are represented by equally spaced vertical lines, and the parallels of latitude are represented by horizontal lines that are closer together near the Equator than near the poles. This uneven spacing compensates for the increasing exaggeration of the east-west distance between adjacent meridians at higher latitudes; this distance decreases on the Earth but remains the same on the chart. See Rosenbach Company, op.cit.

23. See Chisholm, Hugh, ed. (1911), 'Navigation', *Encyclopædia Britannica* 19 (11th ed.).
24. See Michael William Richey, available at http://www.britannica. com/technology/ navigation-technology, (accessed:1 Oct 16).
25. It comprised tables for the simple determination of longitude made by observations of the occultation or eclipses of Jupiter's moons by Jupiter, first seen by Galileo in 1610. See http://www.penobscotmarinemuseum.org/pbho-1/history-of-navigation/navigation-american-explorers-15th-17th-centuries, (accessed:1 Oct 16).
26. The octant is a portable instrument for measuring the angle of the Sun, the Moon, or a star above the horizon. It's name comes from its scale, which is 45 degrees or 1/8th of a circle. See *Navigating at Sea*, Smithsonian Institute, available at https://timeandnavigation.si.edu, USA, (accessed: 20 Oct 2016).
27. The sextant was one of the navigation tools invented in the 18th century by British mathematical instrument makers. It gradually became the symbol of navigation. The device is named for its scale—60 degrees or 1/6th of a circle. See *Navigating at Sea*, Smithsonian Institute, available at https://timeandnavigation.si.edu, USA, (accessed: 20 Oct 2016).
28. See *Navigating at Sea*, Smithsonian Institute, op.cit.
29. See Bedini, Silvio A. *The Pulse of Time: Galileo Galilei, the Determination of Longitude, and the Pendulum Clock.* Florence: Olschki, 1991. See also Vanpaemel, G. 'Science Detained: Galileo and the Problem of Longitude,' *Italian Scientists in the Low Countries in the XVIIth and XVIIIth Centuries,* Edited by C. S. Maffioli and L. C. Palm, Amsterdam and Atlanta, Rodopi, 1989, pp. 111-130.
30. See Navigating at Sea, Smithsonian Institute, op.cit.
31. See Longitude Act, Library of Congress, London, 1714.
32. James Cook used Harrison's chronometer in his campaign around the globe and when he returned in 1779 his calculations of longitude, based upon the chronometer, proved correct to within 8 miles. Consequently, Cook completed very accurate and detailed for his time charts during his voyage, changing the nature of navigation ever since. After that, charts were rapidly developed around the world. See Sobel, Dava, *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time,* New York, Penguin USA, 1996.
33. By 1825, all ships in the Royal Navy were equipped with them. See Ashley Hornish, *National Air and Space Museum*, Smithsonian Institution, available at https://timeandnavigation.si.edu, USA, (accessed: 20 Oct 2016).
34. See Gould, Rupert T., *The Marine Chronometer,* London, Holland Press, 1960. See also Mercer, Vaudrey, *John Arnold & Son, Chronometer Makers, 1762-1843,* London, The Antiquarian Horological Society, 1972 as well as Whitney, Marvin E, *The Ship's Chronometer,* Cincinnati, American Watchmakers Institute Press, 1985.
35. Available at National Museum of American History.
36. The above instrument was made by John Roger Arnold about 1825, as a specialized timekeeper for finding longitude at sea. Ibid.
37. See Michael William Richey, op.cit.
38. As stated by Philip Sadler, this was done by Thomas Hubbard Sumner when, '*after one observation he computed and plotted his longitude at more than one trial latitude in his vicinity – and noticed that the positions lay along a line. Using this method with two bodies, navigators were finally able to cross two position lines and obtain their position – in effect determining both latitude and longitude*'. See Philip Sadler, *Astronomy 2: Celestial Navigation*, Harvard University, USA.

39. Applied celestial navigation usually requires the following aids: 1) a marine chronometer to measure time, b) a sextant to measure the angles, c) an almanac for the schedules of the coordinates of celestial objects and constellations, d) a set of sight reduction tables (Norrie's tables) to help compute height and azimuth, and e) a map of the area. The "reduction" of sextant sights in minutes is performed by small handheld computers, laptops or even scientific calculators. Ibid.
40. See *Navigating at Sea*, Smithsonian Institute, op.cit.
41. See *Popular Science Monthly.*
42. Before that, all of the seafaring nations had their prime meridians, causing longitude to be different on charts created in different countries.
43. See Navigating at Sea, Smithsonian Institute, op.cit.
44. In 1899 the *R.F. Matthews* was the first ship to use wireless communication to request assistance at sea. See Howeth, Captain Linwood S., 'XXXVIII', *History of Communications-Electronics in the United States Navy,* Washington, D.C.: Bureau of Ships and Office of Naval History, 1963 pp. 261–265.
45. See *Dutton, Benjamin, 'Ch.15 – Basic Radio Navigation', Dutton's Nautical Navigation, 15th ed., Naval Institute Press, 2004, pp. 154–163.*
46. This is achieved by their attribute to be unaffected by the ferromagnetic materials of the vessel, most importantly by the ship's steel hull, which affects the magnetic field. See *Merrill, Ronald et all, (1), 'Chapter 8: The magnetic field of the earth: paleomagnetism, the core, and the deep mantle'*, Academic Press, 1996. See also Billur Barshan. 'Gyroscopes', *Wiley Encyclopedia of Electrical and Electronics Engineering*, John Wiley & Sons Inc., 2007, p 547ff
47. See US National Imagery and Mapping Agency, *The American Practical Navigator: An Epitome of Navigation,* op.cit.
48. See Howeth, Captain Linwood S., 'Appendix A: Chronology of Developments in Communications and Electronics'. *History of Communications - Electronics in the United States Navy*, Washington, D.C.: Bureau of Ships and Office of Naval History. 1963, pp. 443–469.
49. See Bedwell, Don (2007), 'Where Am I?', American *Heritage Magazine,* 22 (4).
50. GPS works almost the same way as Loran hyperbolic system (time difference between separate signals), but the signals come from satellites. See National Imagery and Mapping Agency (2001), *Publication 1310: Radar Navigation and Maneuvering Board Manual,* op.cit.
51. See Bedwell, Don (2007), op.cit.
52. See Howeth, Captain Linwood S., op.cit.
53. RDF systems became quite common during the 1960s, under a new name: 'Automatic Direction Finders' (ADFs). *See Kayton, Myron and Walter R. Fried, 'Ch.4 – Terrestrial Radio-Navigation Systems', Avionics Navigation Systems, John Wiley & Sons. 1997, pp. 99–177.*
54. See extensively C. Powell, 'Hyperbolic Origins', *Journal of Navigation*, vol 34. No 3, London, Royal Institute of Navigation. 1981, p. 424.
55. It developed during World War II. It included a series of transmitters sending out precisely timed signals. The signals were leaving the stations at fixed delays. An aircraft using Gee examined the time of arrival on an oscilloscope at the navigator's station. Having the signal from two stations arrived at the same time, it meant that the aircraft should have been in equal distance from both transmitters. In this way it helped the navigator to define a line of position on his chart of all the positions at that distance from both stations. Gee was accurate to about 165 yards (150 m) at short ranges, and up to a mile (1.6 km)y. See *Dutton, Benjamin, op.cit.*
56. Decca was constantly being used on ships from the 50s up to the 90s. See International Hydrographic Bureau, 'Chapter II Decca', *SP 39: Radio Aids to Maritime Navigation and Hydrography*, Monaco, 1962.
57. *See* Pallikaris A., Katsoulis G. and Dalaklis D., *Navigation Electronic Instruments and Electronic Chart Display Information Systems*, 2nd edition, Eugenides Foundation, Athens, 2016, pp. 267-292.

58. By 1962, high-power LORAN-C was in place in at least 15 countries. See Jansky & Bayle, *The Loran-C System of Navigation*, Feb 1962, available at http://www.loran-history.info/Loran-C/Jansky_Bayle_1962.pdf (accessed 20 Sep 2016).
59. *See* Pallikaris A., Katsoulis G. and Dalaklis D, op.cit.
60. See *Dutton, Benjamin, op.cit.*
61. Ibid.
62. Parallel indexing is a technique conceived by William Burger in the 1957. His relevant book is the *The Radar Observer's Handbook*. This technique involves creating a line on the screen that is parallel to the ship's course, but offset to the left or right by some distance. This parallel line allows the navigator to maintain a given distance away from the hazard. See National Imagery and Mapping Agency, *Publication 1310: Radar Navigation and Maneuvering Board Manual,* 7th ed, Bethesda, MD: U.S. Government Printing Office, 2001, pp. 163-169. See also US National Imagery and Mapping Agency, *The American Practical Navigator: An Epitome of Navigation,* op.cit. as well as Maloney, Elbert S., Chapman Piloting and Seamanship, 64th ed., New York, NY: Hearst Communications Inc., 2003.
63. From the 1980s raster-scan synthetic displays, being compliant with the IMO Performance Standards, have been introduced. Their radar picture y is produced on a television screen and is made up of a large number of horizontal lines which form a pattern known as a raster. See United States National Geospatial Intelligence Agency, *Publication 1310: The Radar Navigation and Maneuvering Board Manual, Chapter 5.*
64. Development of ARPA started to emerge in the 60s after a maritime accident when the Italian liner SS Andrea Doria collided in dense fog and sank off the east coast of the United States. Ibid.
65. See Bole, A. et al, *Radar and ARPA Manual,* Oxford, Elsevier, 2005, p. 312.
66. The latest transponder systems (mode S) can also provide position information, possibly derived from Global Navigation Satellite Systems (GNSS), allowing for even more precise positioning of targets. See *Dutton, Benjamin, op.cit.*
67. In 1988, by suitably amending the Safety of Life at Sea (SOLAS) Convention, IMO required ships subject to it fit GMDSS equipment. Ships under those provisions were required to carry satellite Emergency Position-Indicating Radio Beacons (EPIRBs) by August 1, 1993, and had to fit all other GMDSS equipment by February 1, 1999.
68. There are also several other components of this system, such as NAVTEX receivers for navigational and safety warnings, digital selective calling (DCS) MF-HF-VHF devices, satellite systems operated by the Inmarsat company for global coverage distress messages transmission and reception, etc. See IMO, *Handbook on the Global Maritime Distress and Safety System,* 3rd Edition, London, 2001. See also See UK Hydrographic Office, *NP 285: Global Maritime Distress and Safety System,* 2002.
69. COSPAS/SARSAT system uses four geostationary satellites, incorporating GPS receivers to transmit highly accurate positions (within about 20 meters) of the distress position. By the end of 2010 EPIRB had been able to offer AIS (Automatic Identification System) enabled beacons. EPIRB's transmit in 406MHz a registration number which is linked to a database of information about the vessel. See http://www.gmdss.com.au/, (accessed: 1 Oct 16) as well as IMO, *Handbook on the Global Maritime Distress and Safety System,* op.cit.
70. Ibid.
71. See US National Imagery and Mapping Agency, *The American Practical Navigator: An Epitome of Navigation,* op.cit.
72. In fact, the Cold War created new navigational challenges for the military for the latter to be able to response immediately and accurately in a potential worldwide conflict, High-speed fighting aircrafts and bombers as well as ballistic missiles needed better mechanisms to achieve global navigation. See Smithsonian Institution, *Satellite Navigation*, available at https://timeandnavigation.si.edu/satellite-navigation, (accessed: 20 Oct 16).
73. Traditionally, this has been achieved by the use of mechanical gyroscopes and accelerometers. In this respect, one must never forget a basic principle of inertial navigation systems: ‘even the most accurate units “drift” over time. Therefore they require additional periodic navigation fixes. This can be achieved

by connecting them to other navigational systems, namely celestial navigation devices, GPS, or even signals for cell phone networks and wireless access points. Ibid.

74. See Smithsonian Institution, *Satellite Navigation*, op.cit.
75. Ibid.
76. For further details, see National Air and Space Museum, Smithsonian Institution, available at https://timeandnavigation.si.edu/satellite-navigation, (accessed: 20 Oct 16).
77. Several signals with the purpose to decode the location and distance of the satellite are sent by GPS stations while other signals send out the time which is measured by the satellite's onboard atomic clock. Taking measurements from several satellites, the receiver reproduces its own accurate clock signal. Comparing these signals, the distance to the satellite can be produced and several such measurements form a triangulation in order to determine a position on the earth's surface. Ibid.
78. Users can obtain higher accuracy (better than 1cm) by using a second GPS unit at a fixed nearby location (a method called "Differential GPS"). See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, pp. 179-194.
79. For further detail See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch11,12,13.
80. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch11.
81. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch12.
82. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch13.
83. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch9, par.9.8.
84. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch9, par.9.3.2.
85. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, ch1.
86. As of end of 2015, only the US GPS and the Russian GLONASS were globally operational. China is in the process of expanding its regional BeiDou Navigation Satellite System into the global Compass navigation system by 2020, while the EU's Galileo is in an initial phase of global deployment, scheduled to be fully operational by 2020 at the earliest. France and Japan are in the process of developing regional navigation systems as well. See INTERNATIONAL FEDERATION OF AIR TRAFFIC CONTROLLERS' ASSOCIATIONS, (*IFATCA), A Beginner's Guide to GNSS in Europe,* EVP Europe, August 1999.
87. See Official U.S. Government information about the Global Positioning System (GPS) and related topics, Space Segment, available at http://www.gps.gov/systems/gps/space/, (accessed: 20 Oct 2016).
88. See Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, pp. 179-194.
89. See Information and Analysis Center for Positioning, Navigation and Timing, *GLONASS Status*, available at https://www.glonass-iac.ru/en/GLONASS/, (accessed: 1 Oct 2016).
90. See *Beidou satellite navigation system to cover whole world in 2020*, available at http://eng.chinamil.com.cn/, (accessed: 20 Nov 2016).
91. See GPS World: GNSS Position, Navigation, Timing, *isro: all 7 irnss satellites in orbit by March*, available at http://gpsworld.com/isro-all-7-irnss-satellites-in-orbit-by-march/, (accessed: 8 oct 15). See also 'India to have its own gps system soon: isro', *the Hindu* [online], available at http://www.thehindu.com/, (accessed: 4 feb 2016).
92. See Japan's Cabinet Office, National Space Policy Secretariat, *Michibiki: Quasi-Zenith Satellite System*, available at http://qzss.go.jp/en/index.html, (accessed: 20 Nov 2016).
93. Galileo is intended to provide horizontal and vertical position measurements within 1-metre precision and ameliorated positioning services at high latitudes with regard to other positioning systems. See Van Der Jagt, Culver, *Galileo: The Declaration of European Independence*, Royal Institute of Navigation, 7 November 2001. See also *On a Civil Global Navigation Satellite System (GNSS) between the European Community and its Member States and Ukraine,* available at https://www.gov.uk/government/uploads/system/uploads/, (accessed: 12 Jan 2015).
94. See Dee Ann Divis, 'Military role for Galileo emerges', *GPS World*, May 2002, Vol. 13, No. 5, p. 10. See also Jaizki Mendizabal et al, *GPS and Galileo,* McGraw Hill, 2009.

95. For a detailed view on Electronic Charts and ECDIS see Pallikaris A., Katsoulis G. and Dalaklis D, op.cit, pp. 305-380.

96. See *International Hydrographic Organization* (IHO), *S-57: Transfer Standard for Digital Hydrographic Data* as well *as S-52: Specifications for Chart content and display aspects of ECDIS, available at* http://www.iho.int/iho_pubs/IHO_Download.htm, (accessed: 20 Sep 16).

97. See IHO*, Introduction to Electronic Chart Systems and ECDIS*, available at http://www.iho.int/, (accessed: 20 Sep 16).

98. IHO Publication S-61 provides guidelines for the production of raster data. See IHO, S-61: Product Specification for RNC, *available at* http://www.iho.int/iho_pubs/IHO_Download.htm, (accessed: 20 Sep 16). IMO Resolution MSC. 86(70) permits ECDIS equipment to operate in a Raster Chart Display System (RCDS) mode in the absence of ENC.

99. See IHO*, Introduction to Electronic Chart Systems and ECDIS*, op.cit.

100. An ECDIS system displays the information from electronic navigational charts (ENC) or Digital Nautical Charts (DNC). It integrates position information from position, heading and speed through other navigational sensors such as radar, fathometer and Automatic Identification Systems (AIS). There are also other sensors able to interface with an ECDIS such as radar, Navtex, depth sounders, etc. See Weintrit Adam, *The Electronic Chart Display and Information System (ECDIS). An Operational Handbook*, CRC Press, Taylor & Francis Group, London, 2009. See also http://www.ecdis-info.com/about_ecdis.html, (accessed: 15 Nov 16).

101. ECDIS is defined in the IMO ECDIS Performance Standards (IMO Resolution A.817(19)) as follows: "*Electronic Chart Display and Information System (ECDIS) means a navigation information system which, with adequate back up arrangements, can be accepted as complying with the up-to-date chart required by regulation V/19 & V/27 of the 1974 SOLAS Convention, by displaying selected information from navigation sensors to assist the mariner in route planning and route monitoring, and by displaying additional navigation-related information if required".*

102. In International Standard IEC 61174. See *International Electrotechnical Commission, Maritime navigation and radiocommunication equipment and systems – Electronic chart display and information system (ECDIS) – Operational and performance requirements, methods of testing and required test results'.*

103. For an extra view at the operational use of AIS Transponders see IALA, *Guideline No. 1028: on the Automatic Identification System (AIS),* Volume 1, Part I: Operational Issues, Edition 1.3, International Association of Marine Aids to Navigation and Lighthouse Authorities Dec 2004.

104. They in fact constitute an automatic tracking system that is mainly used on ships and by vessel traffic services (VTS). Its purpose is to identify and locate vessels by electronically exchanging data with other nearby ships, shore stations and satellites. See http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx, (accessed: 30 Sep 16).

105. Such as a gyrocompass or rate of turn indicator etc. See The Navigation Center of Excellence, *How AIS Works*, US Department of Homeland Security, US Coast Guard, available at www.navcen.uscg.gov, (accessed: 20 Nov 16).

106. See The Navigation Center of Excellence, *What is AIS*, US Department of Homeland Security, US Coast Guard, available at www.navcen.uscg.gov, (accessed: 20 Nov 16).

107. See IMO, *Resolution MSC.74(69), Annex 3: Recommendation on performance standards for a universal Shipborne Automatic Identification System (AIS).*

108. See Chrysochou G., 'International and European Maritime Environment Safety Framework and Related Control Systems', *Academy of Strategic Analyses,* Working paper, No 43, March 2016, ISSN: 2407-9863.

109. The AIS standards include certain automatic calculations based on these position reports. Suggestively, one may mention the Closest Point of Approach (CPA), collision alarms etc. Furthermore, AIS is usually used in conjunction with radar.

110. See http://www.imo.org/en/OurWork /Safety/SafetyTopics /Pages/ Integrated Bridge Systems.aspx (accessed: 12 Sep 16).

111. The revised SOLAS chapter V adopted in December 2000 and entered into force in July 2002 says in *Regulation 19: Carriage requirements for shipborne navigational systems and equipment paragraph 6:* "*Integrated bridge systems shall be so arranged that failure of one sub-system is brought to immediate attention of the officer in charge of the navigational watch by audible and visual alarms, and does not cause failure to any other sub-system. In case of failure in one part of an integrated navigational system, it shall be possible to operate each other individual item of equipment or part of the system separately*".
112. See IMO Resolution MSC.64(67), Annex 1, *Recommendation on performance standards for Integrated Bridge Systems (IBS).*
113. In most ships, an additional alarm connected to the IBS is also fitted in the cabins of navigational officers. This alarm produces a signal in the cabins within 30 seconds in case the officer in charge fails to acknowledge any alarm.
114. See http://www.marineinsight.com/marine-navigation/what-is-integrated-bridge-system-ibs-on-ships, (accessed: 12 Sep 16).
115. See IMO SN Cir. 265, *Guidelines on the application of SOLAS Regulation V/15 to INS, IBS and Bridge Design,* Oct 2007.
116. See International Maritime Organization (IMO) official website, available at http://www.imo.org.
117. See International Hydrographic Organization (IHO) official website, available at http://www.iho.shom.fr
118. See International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) official website, available at http://www.iala-aism.org.
119. See IMO Resolution MSC.86(70), Annex 3, *Recommendation on performance standards for an Integrated Navigation Systems (INS).*
120. See IMO Resolution MSC.64(67), op.cit.