How Would Bowditch Navigate Today? The Centuries-Old Quest for Resilience in Navigation

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ABSTRACT

In 1802 Nathaniel Bowditch forever changed the world of maritime navigation with publication of The New American Practical Navigator. *As a navigator in his day and throughout his book, Bowditch brought resilience to the art of navigation. In the modern age of GPS, navigation may seem like a solved problem. However, recent concerns about the availability and integrity of GPS and the safety of life at sea call for a sober examination of the resilience of modern navigation systems.*

INTRODUCTION

Mention the name Bowditch to any sailor who has been to sea as a navigator, and you are bound to receive a smile or a grimace. In 1802, Nathaniel Bowditch wrote *The New American Practical Navigator*. Revisions are still published today, and the work has come to be affectionately known as The Navigation Bible or, simply, Bowditch. At a time when dangerous accidents were common, this book made safe and accurate navigation accessible to sailors who had little formal training in mathematics or the sciences of astronomy, meteorology, or geodesy. Encouraging competency of the crew, diligence in record-keeping, and focus on using all sources of information available to determine one's position, Bowditch introduced the concept of resilience into navigation over 200 years ago.

Today's navigators have the benefit of technological advances that make it easier than ever to determine position. At the same time, they face maritime missions that require more precise knowledge of navigation information (position, velocity, attitude, and time) than ever before—more precision than Bowditch could have imagined. To ensure accuracy and availability of these data, as well as the safety of the ships and the personnel they carry, resilience must be built into the systems that provide these services.

WHO WAS NATHANIEL BOWDITCH?

Nathaniel Bowditch (Fig. 1) was born in Salem, Massachusetts, in 1773 to a seafaring family. While he showed an early aptitude and interest in mathematics, he never completed a formal education. His family's poverty forced him to leave school for work at age 10, and at 12 he was indentured to the first of two masters. Working as a bookkeeper in a ship's chandlery, young Bowditch learned about the tools of the trade and even built himself crude versions of several tools, including a Gunter's scale (a 2-ft. rule), a barometer, a sundial, and a Gunter's quadrant (precursor to the sextant; see Fig. 2). Fortunately for Bowditch, his employers did not

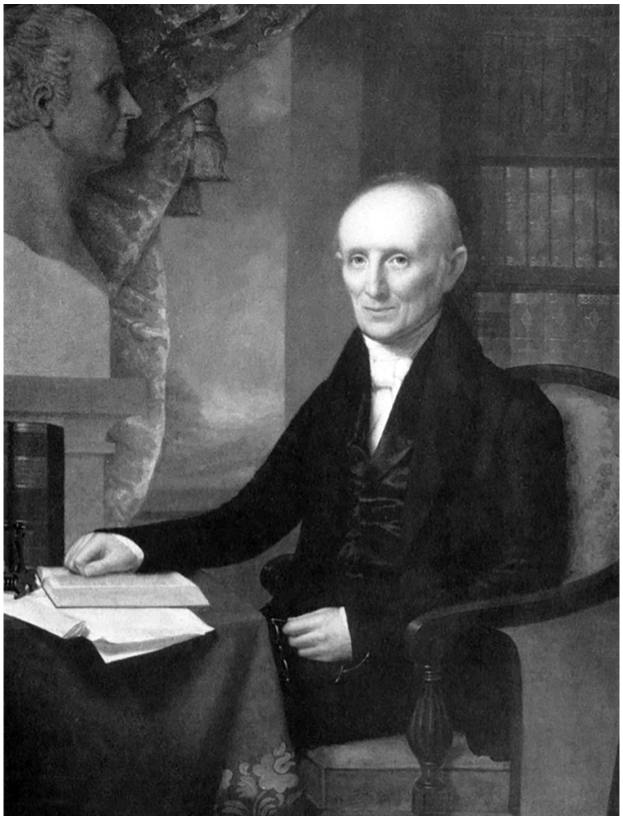


Figure 1. Portrait of Nathaniel Bowditch by C. Osgood. (Photograph, Peabody Essex Museum.)

discourage him from learning during his free time or even on the job when days were slow. Aided by books loaned to him by learned men in town, Bowditch taught himself algebra and calculus, as well as several languages so that he could study foreign books. To study physics, he first taught himself Latin so that he could read Isaac Newton's *Principia* (*Philosophiae Naturalis Principia Mathematica*). He even found an error in the text but lacked the confidence to announce the error until many years later. As a young teenager, Bowditch studied both navigation and surveying and was recruited to assist in a survey of the town. When he was 18, two local ministers persuaded the Philosophical Library Company to allow him to use its books. At 21, when his apprenticeship ended, Bowditch was well regarded as one of the foremost mathematicians in the country.[1]

Bowditch first went to sea at age 21 as a bookkeeper. Because having a dedicated crew member as a bookkeeper was a luxury at the time, he was also assigned the role of second mate, nominally the ship's navigator. At the time, marine charts were inaccurate, sometimes dangerously so. More informative than the available charts were the logs from other ships' voyages. These told of weather patterns, currents, landforms, and pirates and described how the ships dealt with these challenges. Before his journeys, Bowditch studied the logs from previous voyages.

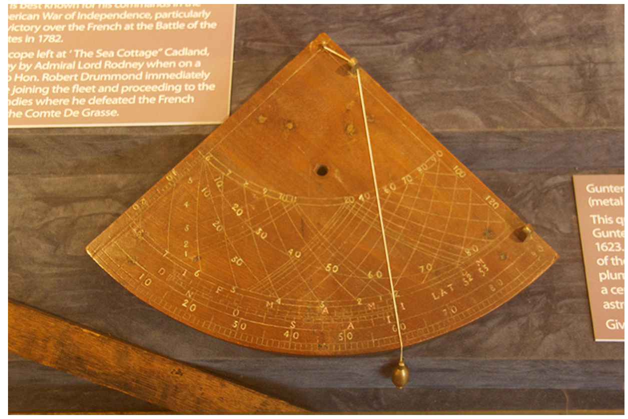


Figure 2. Gunter's quadrant, a simplified version of an astrolabe, precursor to the sextant. (Photograph by Mike Peel, www.mikepeel.net; CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0.)

Another obstacle to navigation at the time was the lack of accurate timekeeping. In the time of Bowditch, marine navigation was commonly performed by a combination of sailing by lines of latitude, in which the vessel would sail north or south to the desired latitude and then transit longitudinally to the destination, and dead reckoning, in which speed and direction were measured over time to obtain position. Speed was measured by tossing overboard a log tied to a rope. The rope had knots tied in it at specific distances; the log was used to keep the rope afloat. Crews would use an hourglass of known duration to count how many knots were paid out in the period of measurement. Thus, they had distance per given time and invented a new term for measuring speed, *knots*. However, this method of determining position was imprecise at best, and ocean currents, which can cause a ship's track to differ from its heading, were an added source of error.

While celestial navigation can give one's latitude without accurate knowledge of global time, longitude is inherently related to time and cannot be derived without it (see Box 1). The problem of finding longitude was such a critical scientific challenge that in 1714, England's parliament offered a reward to anyone finding a successful solution.[2] Within a few decades, carpenter and clockmaker John Harrison had developed a successful marine chronometer; unfortunately, by the time Bowditch was sailing, the cost was still prohibitive for merchant vessels. An alternative method of determining time at sea was the calculation of lunar distance, or, simply, "lunars." These calculations were mathematically intensive and relied on accurate almanacs for finding longitude. Many ships' crews did not attempt them.

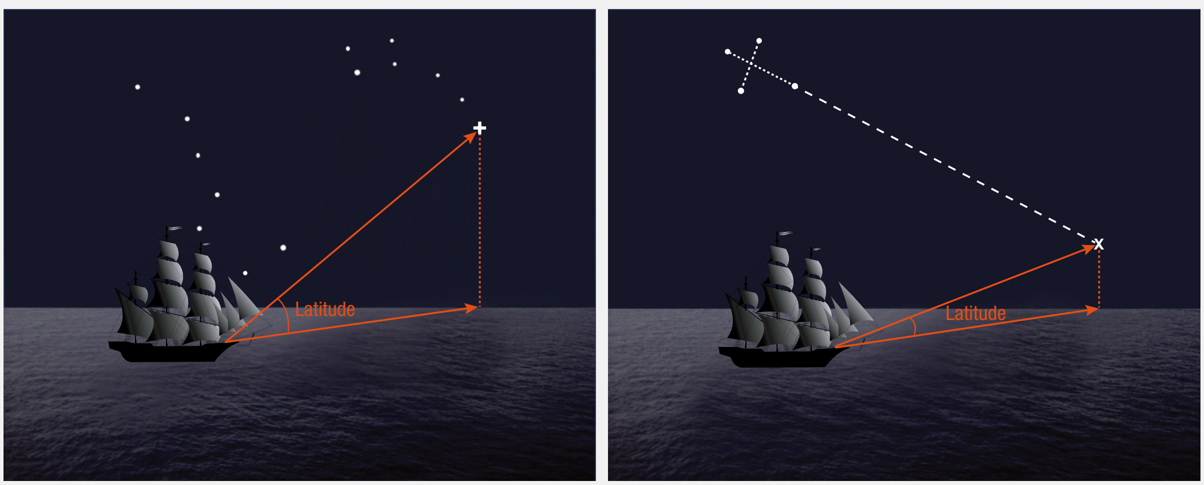
Bowditch not only calculated lunars to correct his ship's position, but he also taught the entire crews to calculate them. More than once the captain of his ship was able to proudly announce that every one of his men could perform the lunar calculation, and at least once a ship's cook was called out to demonstrate. As Bowditch took more accurate position measurements, he made corrections and improvements to the existing nautical charts.

At the time, the foremost book on navigation was written by John Hamilton Moore of England. Unfortunately, his book, *The Practical Navigator*, contained some 8,000 errors, some of which had been deadly for ships. The American publisher of the book, Edmund Blunt, first asked Bowditch to produce a revision and later suggested he write his own book. Thus was born *The New American Practical Navigator* (see Fig. 3). Bowditch did not include any information from Moore's book that he could not independently verify. He recalculated every table and added new ones, and included a wide variety of instruction in maritime subjects. He also included a new method to calculate lunars that he had developed himself.

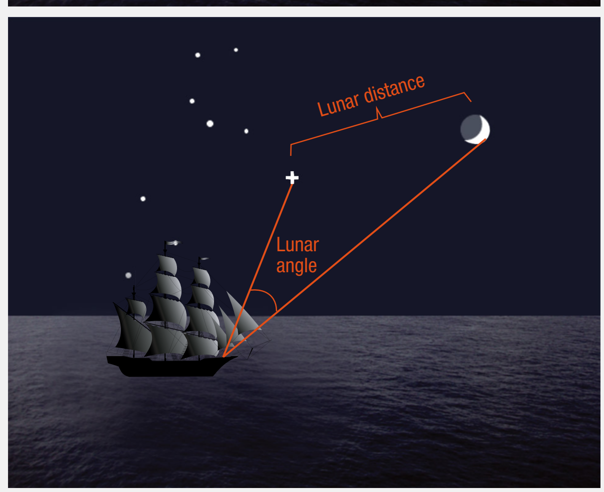
Nearly as important as the accuracy of Bowditch's book was its accessibility to the average sailor, who was not educated in subjects such as algebra and trigonometry. If the book could not be understood by an everyday ship's crew, it would not be used. Finding the layout of Moore's book to be a logical flow of information, Bowditch retained the layout for his own book. To introduce mathematical concepts, he started with an explanation of how to perform arithmetic with decimals. He included instructions on how to use a Gunter's scale and sector and how to calibrate a watch. He included a 14-page glossary of sea terms. He also explained how to keep an annotated ship's log. Within a few years of the

BOX 1. CELESTIAL NAVIGATION

Determining latitude is the easier of the two measurements. In the Northern Hemisphere, the measured angle between the North Star and the horizon roughly gives the navigator's latitude. The Southern Hemisphere has no pole star, so the position of the south celestial pole can be estimated by extending the line of the Southern Cross roughly 4.5 times its length. Alternatively, latitude can be determined in either hemisphere by measuring the angle to the sun at solar noon (when the sun is highest in the sky) and adding or subtracting with the sun's declination.



Determining longitude is more of a challenge, because the positions of the celestial bodies vary with time as well as with longitude. Thus, the navigator must determine time before calculating longitude. In the absence of an expensive marine chronometer, the method of lunar distance was used. The navigator had to measure the angle between the moon and another celestial body, commonly the sun or the star Regulus. Correcting for parallax and the semidiameter of the celestial bodies (since the navigator had to measure from the edge of the body rather than the center) gave the lunar distance, which varied with time. An almanac gave the time in Greenwich, where longitude = 0, for a given lunar measurement. This was compared with the apparent solar time, which could be estimated by the altitude of the sun or a star. The difference in time was multiplied by 15° per hour (the Earth's rotational rate) to give the navigator's longitude.



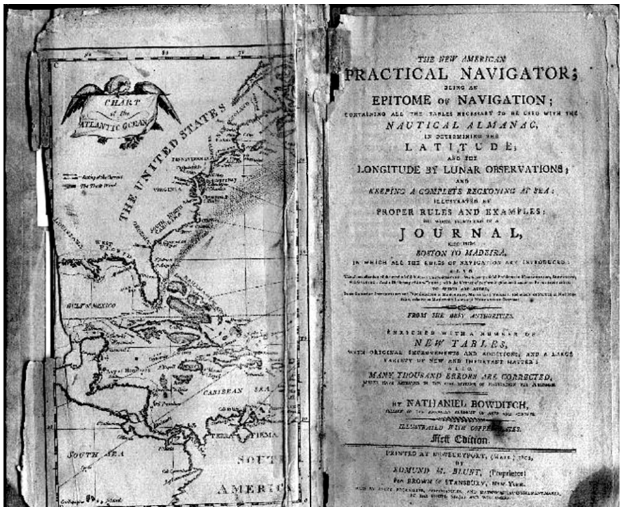


Figure 3. First edition of Bowditch's *The New American Practical Navigator.*

publication of Nathaniel Bowditch's book, celestial navigation became common on American ships.

EVOLUTION OF NAVIGATION FROM BOWDITCH TO GPS

The tools available to Bowditch were the marine chronometer (1735), the sextant (1757), and the nautical almanac (1766). After publication of his book, these tools became the standard for marine navigation, and techniques for determining position remained largely unchanged for the next century.

With the advent of the airplane in 1903, and its development through two world wars, many navigation aids and capabilities were created to support the unique needs of air navigation. Transcontinental marine navigation remained largely unchanged, however, with the exception of the addition of radar navigation and the gyrocompass. Radio-based position fixing was not globally available.

Then, in the 1950s, two events changed the marine navigation status quo, and both were related to submarine developments and the Cold War between the United States and the Soviet Union.

First, launch of USS *Nautilus* in January 1954 debuted the world's first nuclear-powered submarine, which demanded a navigation suite that would support its full capability of continuous submerged operations. Construction was finished in 1955, and the *Nautilus* completed the first submerged transit of the North Pole on 3 August 1958, with the first shipborne inertial navigation system (INS).

Second, the Soviets' launch of Sputnik in October 1957 started the space race, as Sputnik demonstrated the potential to field a ballistic missile capable of reaching the United States. This fear led to development of American intercontinental ballistic missiles, including those that could be launched from specially configured submarines. USS *George Washington*, the first U.S. submarine with this capability, entered service in 1959 and conducted the first submerged test launch of a submarine-launched ballistic missile in 1960.

Position accuracy at launch is critical to a ballistic missile's performance. To support the emerging concept of nuclear deterrence, the shipborne INS required periodic updates to maintain navigation accuracy. The idea for the first space-based navigation system was born at the Johns Hopkins University Applied Physics Laboratory (APL) in 1957, as scientists listened to the radio signals from Sputnik (see Fig. 4). Using the received signals and the known position of the antenna at APL, APL scientists devised a method to calculate the orbit param-

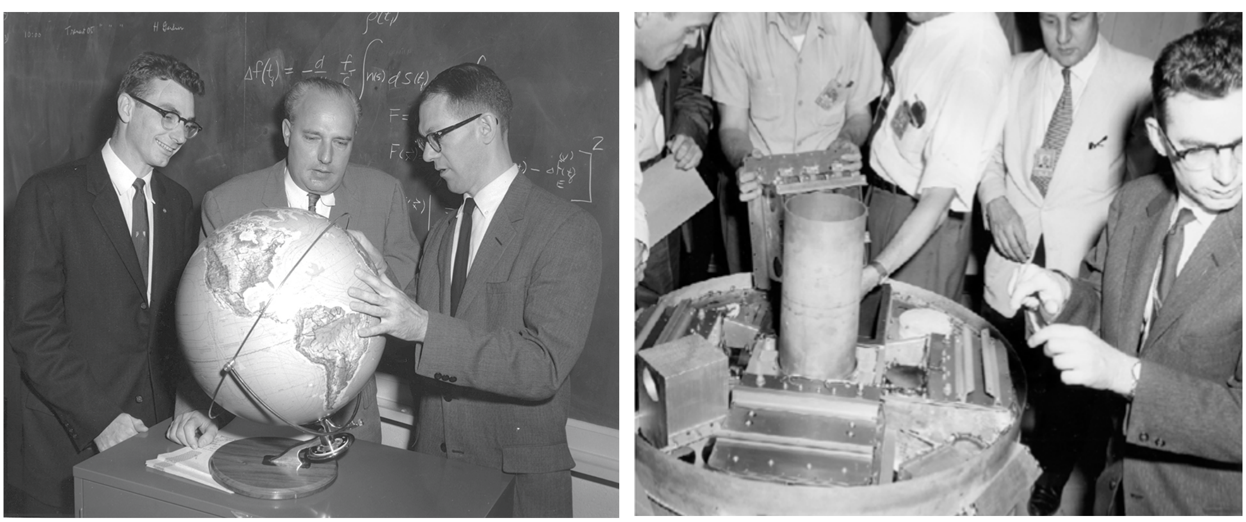


Figure 4. Left, Drs. William Guier, Frank McClure, and George Weiffenbach, who first conceived of satellite navigation. Right, Transit 1A satellite.

eters from a single Doppler shift of the received signals as it passed overhead.

It occurred to the APL scientists that if you knew the orbit parameters and measured the Doppler shift, you could fix your position at sea with one satellite. This approach was determined to be viable and practical using the technology available at the time. Thus was born the age of worldwide satellite navigation. The first satellite of the Navy Navigation Satellite System, or "Transit," was launched in 1958. By 1964, the Navy was using radio signals from its own satellites to navigate submarines and surface ships worldwide. In 1967, Transit became commercially available and remained in service until 1996.[3]

While Transit met many military needs, it had several severe drawbacks: chief among them were that fixes were not continuously available. Based on World War II developments, a hyperbolic radio system based on very low frequency (VLF) signals transmitted from huge land-based towers was developed. This internationally developed system, named OMEGA, became operational in 1971 and made worldwide fixes continuously available, although with reduced accuracy compared with Transit.

All navigation systems to date had limitations in accuracy, availability, usability, and affordability. The long-range navigation system LORAN-C was continuous and had modest accuracy, but it was not worldwide and was subject to weather degradation and dependence on partner nations. OMEGA was worldwide and continuous, but it was not accurate for military operations and also depended on partner nations. Transit was worldwide and U.S. owned and managed, but it was not continuous and fixes often took a long time. Inertial navigation is worldwide and continuous, but high-accuracy systems are very expensive and still require occasional external fixes to maintain performance. Celestial fixes are worldwide but are not continuous or accurate, and they are weather dependent. Although they are not expensive, they come with a large learning curve for users.

The NAVSTAR system, later renamed GPS, was conceived in 1963 and was designed to provide everything the military needed for future conflicts. The military needed small, inexpensive, receive-only systems that could operate in all weather and provide global coverage, high accuracy, and high update rates. Additionally, modern communications systems now required accurate time. GPS was designed to meet all of the DoD's positioning, navigation, and timing (PNT) needs; the term *PNT* was coined to describe the system's purpose. By 1974, the first GPS satellite was launched. By 1990, the system was operational; it reached full operational capability by 1995, meeting or exceeding all expectations.

PARADIGM SHIFT IN NAVIGATION

After GPS became fully operational, the U.S. military accelerated widespread adoption of the technology into platforms and weapons. Civilian users were slower to adopt GPS, mainly because of the selective availability function, which degraded civilian GPS signals in order to protect the most accurate capability for military users only. That all changed in May 2000, when President Bill Clinton ordered removal of the GPS selective availability function,[4] allowing civilian users to enjoy the same precise positioning and timing information that the military had access to. To say that civilian users embraced GPS technology would of course be a vast understatement. GPS receivers are in our homes, cars, and mobile phones. Today GPS provides precise position and timing information for the nation's critical infrastructure[5] and is itself critical to the security of our nation.

GPS was a boon to navigation, and as confidence in it grew, the need for other navigation sources became less critical. For example, celestial navigation was removed from the curriculum at the United States Naval Academy, LORAN stations were turned off in the United States,[6] soldiers stopped carrying paper maps and compasses and instead relied on GPS and digital maps, and system designers stopped including clocks in systems that needed time, using inexpensive GPS receivers instead.

While further navigational equipment continued to be installed on ships, these additional components were generally meant to fill gaps in capabilities that were not provided by GPS. For instance, fathometers tell the ship the depth of water below its keel. Radars provide range and, to some extent, bearing to landforms or other ships, while the GPS-based Automatic Identification System alerts the crews to the positions and identifications of other ships on the water. An electronic charting display and information system provides precise marine charts and enables voyage planning. Electromagnetic logs provide speed through the water. None of these systems provided absolute position, velocity over ground, or time to serve as backup sources to GPS. Except for on submarines, which cannot use GPS when submerged, INSs were primarily used for their attitude output only and were often not maintained or groomed to provide accurate position.

Thus, while GPS revolutionized navigation, its adoption and implementation led to a decrease in overall navigation resilience. One could argue that the practice of navigation became a dying art.

RECENT CONCERNS: NAVWAR AND SAFETY

Over several days in June 2017, multiple commercial vessels in the Black Sea reported that their GPSs were displaying the same incorrect position, placing them instead in the area of a Russian airport (see Fig. 5). In addition, the ships reported that their GPS position periodically jumped from one location to another.[7]

The incident, which became known in the Navy as the Black Sea Event, displayed hallmarks of a GPS

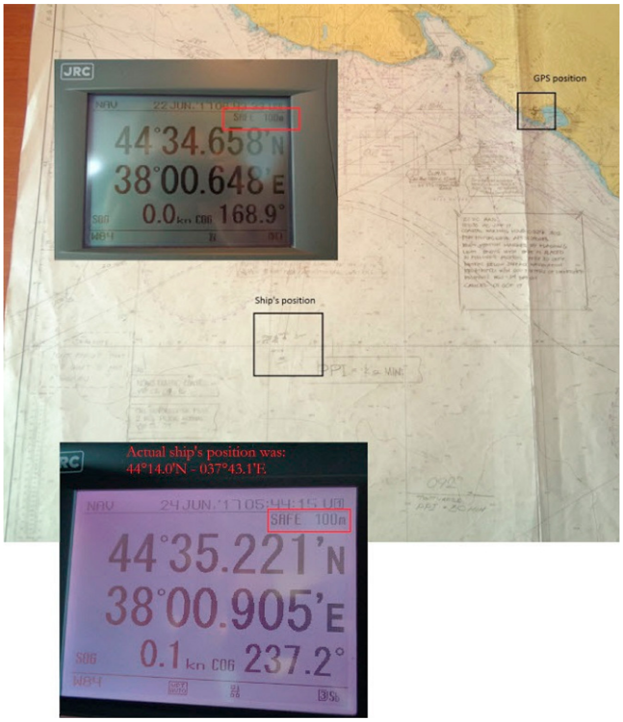


Figure 5. Actual and GPS-reported positions of one ship in the Black Sea.

spoofing attack. Spoofing is when a simulated GPS signal containing erroneous navigational information is broadcast with the intention that it will be accepted as truth by GPS receivers. While the Black Sea Event was not the first known incident of spoofing, it was perhaps the most well publicized. Although there were questions about whether the incident was caused by intentional spoofing or unintentional receipt of a simulated signal,[8] the event nevertheless highlighted the vulnerability of GPS to hostile or accidental interference (see Fig. 6).

The weaknesses and vulnerabilities of GPS were known at the time it was initially designed.[9] The frequency choice (L-band) and weak signal do not allow the system to be used indoors, underground, under tree canopies, or underwater, and they also make accidental or intentional interference extremely easy.[10] Additionally, the civilian GPS signal structure is well known and extremely susceptible to spoofing by malicious actors. In 2013, University of Texas aerospace engineering students successfully spoofed GPS when they captured the GPS receiver on the luxury yacht *White Rose* and steered the ship miles off course.[11] They later captured the receiver on an unmanned drone and landed it on the football field at the University of Texas. While demonstrated GPS spoofing cases are rare, the prevalence of software-defined radios with GPS simulators makes GPS spoofing of unencrypted civilian signals very easy.

GPS spoofing is one type of navigation warfare, or NAVWAR. NAVWAR is defined by the military as "the deliberate defensive and offensive action to assure and prevent PNT information through coordinated employment of space, cyber space and electronic warfare operations."[12] In addition to GPS spoofing, hypothetical offensive NAVWAR attacks include GPS and other radio frequency jamming, cyberattacks inserting malicious code or false information into navigation systems, and even kinetic attacks targeting a vessel's navigation system, GPS satellites, or ground stations. While the concept of NAVWAR has been known to the military for at least two decades,[13] it is only in recent years that the idea has transitioned to policy, such that military navigation systems are required to be NAVWAR compliant to maintain a navigational advantage during military operations.[14]

NAVWAR was not the only marine navigation concern publicized in 2017. Four Navy ship collisions,

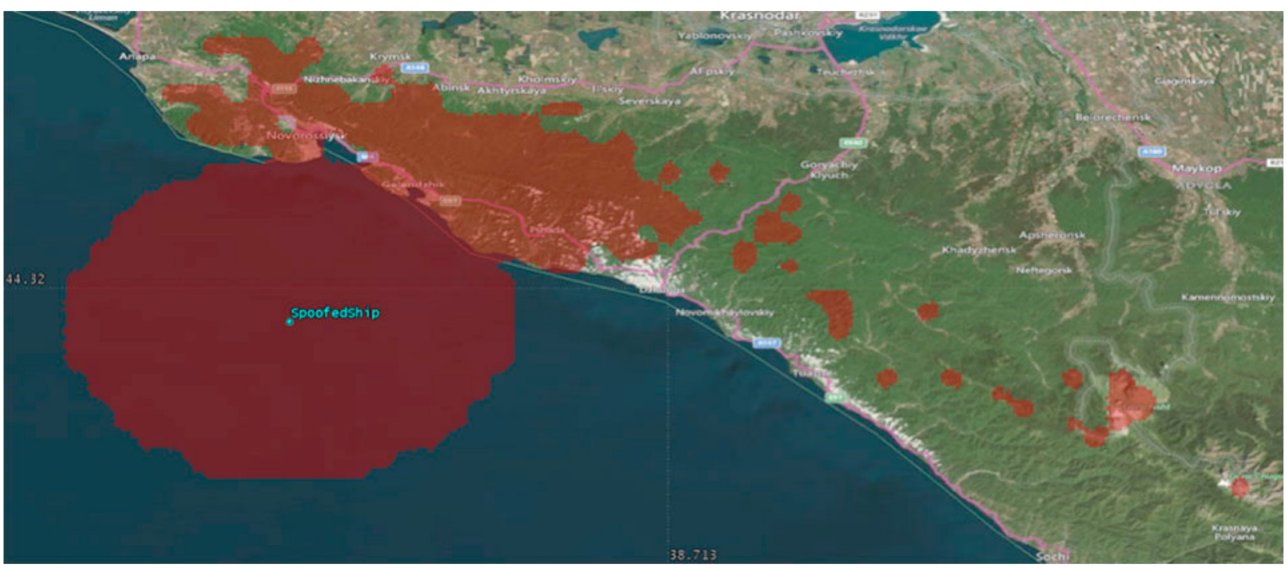


Figure 6. Possible spoofing source locations, based on terrain and assumed mast heights.

Figure 7. Port side of USS *John S. McCain* after a collision with an oil tanker on 21 August 2017. (U.S. Navy photo by Mass Communication Specialist 2nd Class Joshua Fulton/Released.)

beginning with USS *Antietam* running aground in January and culminating with USS *John S. McCain* (Fig. 7) colliding with a merchant vessel in August, brought issues of situational awareness and navigational safety into the spotlight. The last two collisions, including the USS *Fitzgerald* crash in June, took the lives of 17 U.S. sailors.

None of these events were caused by incidents of NAVWAR or failure of navigational equipment. Rather, the primary cause in all cases was human error. The comprehensive review of the incidents states:

> In each incident, there were fundamental failures to responsibly plan, prepare and execute ship activities to avoid undue operational risk. These ships failed as a team to use available information to build and sustain situational awareness on the Bridge and prevent hazardous conditions from developing. Moreover, leaders and teams failed as maritime professionals by not adhering to safe navigational practices.[15]

Figure 8. Quartermasters on USS *Boxer* plot the ship's course using digital and paper charts. The Navy is working to integrate navigational information from more sources into common displays on the bridge. (U.S. Navy photo by Mass Communication Specialist Seaman James Seward/Released.)

Several factors were suggested to have contributed, from too many onboard assessments during maintenance periods to failure to manage crew stress and fatigue. Many findings cited deficiencies in crew training for seamanship and navigational skills. Notably, one contributing factor was the lack of standardized, integrated situational awareness tools on the bridge. While ships are equipped with numerous sensors to ensure safety of navigation, such as radars, Automatic Identification System, electronic charts, fathometers, and current and wind monitors, these tools are not integrated into common displays and communication systems that allow crews to easily assimilate multiple sources and make informed decisions.

The Navy is actively engaged in addressing the concerns about NAVWAR and safety of navigation (see Fig. 8). In the era of GPS, what changes should the Navy make to ensure that ships' navigation systems, both hardware and personnel, can overcome obstacles to navigate in all situations and environments—that is, to ensure that navigation is resilient?

HOW WOULD BOWDITCH ENSURE RESILIENT NAVIGATION TODAY?

In the time of Bowditch, the role of navigation was to enable a ship to pass safely from point to point. While that may still be the sole role of navigation for many commercial vessels, navigation's role for the military has expanded (see Box 2). In addition to ensuring efficient passage of ships and the safety of life at sea, today's navigational equipment is responsible for supplying position, velocity, attitude, and timing data to communications, reconnaissance, combat, and other systems that carry out the missions of Navy ships.

In his own time and within the bounds of the available technology, Nathaniel Bowditch created resilience

BOX 2. WHAT NAVIGATION MEANS TODAY

Navigation refers to the determination of both absolute and relative positions, velocities, and attitudes; point-to-point voyage planning; and arrival prediction. It encompasses techniques, sensors, clocks, associated computers and networks, and charting. Safe and accurate marine navigation requires the determination of horizontal position, altitude or depth, heading, roll, pitch, yaw, velocities with respect to ground, speed with respect to water, environmental factors such as ocean currents and gravity, platform accelerations, precise time or timing frequency, and positions and motions of navigational hazards. Outputs of a navigation system are used both for safe ship control and by other ships' systems that require position, velocity, attitude, or timing information to support their missions.

in navigation. If faced with today's navigational mission and given today's technology, how would he choose to navigate?

Without a doubt, Bowditch would have employed GPS. He favored lunars over dead reckoning with a rope and log because the lunars were more accurate, and increased accuracy led to increased safety. GPS enhanced both safety of navigation as well as the ability of Navy ships to carry out missions that required highly accurate navigation data. Given what is known about Bowditch's desire to learn and understand, at the advent of GPS he likely would have researched the technology until he felt comfortable with the science and saw demonstrations of its ability compared with other navigation techniques. He would have also made sure to understand its risks, and he would have adopted proven technologies, such as the enhanced antennas and encryption being implemented by the Navy, to help mitigate those risks.

While adopting GPS, however, Bowditch would have maintained alternative navigation sensors onboard, and he would have made sure his crews were trained in their use. While Bowditch advocated for using lunars, he did not end the practice of dead reckoning onboard his ships. He recognized that backup systems were necessary because no single method works perfectly in all situations or environments. This is as true today as it was centuries ago.

Today, when pursuing a backup to GPS, the most robust is the INS. It has global coverage, including underwater, and works 24 hours a day. In its fundamental form, it does not rely on any outside signals for operations, so it cannot be jammed or spoofed. In practice, though, the INS does develop errors over time, and it takes in data from outside sources, including GPS, to help control those errors. The long-term accuracy of an INS is highly dependent on the quality of its sensors, primarily the gyroscopes. Some INSs are able to maintain accuracy for hours, days, or weeks without an external correction, but as accuracy increases, so does the cost; the most accurate INSs are unaffordable for many commercial vessels and even some military ships. In pursuit of the next generation of INSs, DoD must continue to fund ongoing research in areas of atomic interferometry and quantum gyros. Advances in gyro technologies[16] have the potential to revolutionize maritime navigation resilience by providing continuous, accurate navigation data that is invulnerable to many forms of NAVWAR.

Short of new gyro technologies, existing INSs can be made more accurate with external sensor inputs to help manage errors. Currently the two most common inputs to the INS on Navy ships are GPS and a log that provides speed through water. Because of the threat of NAVWAR attacks on GPS, alternative sources need to be considered for use on maritime platforms. Such sources might include other radiofrequency signals, such as Enhanced Long-Range Navigation (eLORAN), VLF, and alternative satellite navigation; geophysical navigation methods such as bathymetry (bottom contour navigation), gravimetry, magnetometry, and celestial navigation; signals of opportunity such as local television or radio signals; and measures of bottom track velocity such as those that can be achieved through Doppler velocity logs or correlation sonars. Some of these technologies are fully developed and ready for use; others require infrastructure, technology maturation, or policy changes before they can achieve operating capability. The key is that not every technology or method needs to be adopted—only enough so that accuracy is maintained through a wide variety of environmental and threat conditions.

In addition to backup position sources, alternative sources of precise time are needed to maintain resilient navigation systems. Currently, rubidium oscillators are the primary standard on Navy ships; they provide a stable backup time source with a fairly predictable drift rate. A switch to more precise cesium oscillators, from which the definition of a "second" is currently derived, would improve long-term time stability in the absence of GPS. Advances in quantum technologies could improve atomic timekeeping to the point that external time synchronization is unnecessary during the course of an average patrol.[17,18] Or alternative satellite or multiway satellite time transfer may provide a backup to GPS time.

By all accounts, Nathaniel Bowditch had high mathematical aptitude and educated himself in the mathematics of navigation. It is easy to imagine that today he would be an expert in fields such as signal processing, parameter estimation, and sensor fusion. The algorithmic solutions developed by experts in these fields can help optimize system performance by filtering the "true" signal from noise and providing estimates of a system's uncertainty so that the system itself can make corrections to enhance its performance. Some forms of mathematical optimization already occur on Navy vessels; for instance, an INS uses Kalman filters to integrate external inputs into its solution. More can be done, however. Such solutions involve software only, making them less expensive to implement than new hardware.

The concept of NAVWAR did not exist in Bowditch's day, but mariners did face threats aside from environmental hazards. Pirates were prevalent, and sailing the same known routes along lines of latitude made ships easy targets. By improving navigation methods, Bowditch reduced mariners' risk of falling victim to pirates in addition to reducing their risk of groundings and collisions. By reading the logs of other ships' voyages, he gained insight into previous encounters with pirates. Diligent log keeping is no less important today for recording and sharing knowledge than it was in the days of Bowditch, and it should be accompanied by effective channels for reporting system malfunctions and acquiring solutions to those problems.

It is reasonable to assume that Bowditch would apply the same need for situational awareness about pirates to situational awareness about NAVWAR. NAVWAR monitoring is needed on ships to ensure that navigation solutions do not get corrupted, as well as to alert warfighters to hostile threats so that they can take appropriate defensive or offensive actions. NAVWAR monitoring may be accomplished through a combination of observing individual sensors' signals and comparing parameters to expected baselines, comparing multiple signals to detect whether one or more is anomalous, and establishing cybersecurity measures that control the passage of data and alert the ship to unknown messages. Although the Navy has not yet fully implemented protections against NAVWAR, it is actively pursuing improvements to cybersecurity and investigating methods of detecting GPS jamming and spoofing. One particular NAVWAR monitoring capability, the integrated position, navigation, and timing (iPNT) system developed at APL, has already been installed for extended testing on a submarine, with plans for implementation on the rest of the submarine fleet.

Bowditch's *The New American Practical Navigator* was revolutionary in its day because it allowed mariners to navigate with accuracy and ease and to feel confident in their ship's safety. Today's navigation systems provide a high degree of accuracy, but improvements can be made to their ease of use. As the comprehensive collision report noted, bridge systems do not have a standard configuration, do not fully integrate all sensors for situational awareness, are not modernized to handle reduced crew size, and have not been designed with human–system interface in mind. In this area, the report notes, commercial vessels may actually fare better than military vessels, as commercial bridges are designed with navigation, rather than combat, in mind. Redesigned integration among navigation sensors, the bridge, and human watch standers would improve communication, situational awareness, and overall ship safety.

Finally, Bowditch ensured that his ships' crews could use the tools and perform the calculations to determine their position. Today's military and commercial fleets must do the same. Crews should have a basic understanding of how each system operates and how multiple systems are integrated. They should be trained to properly calibrate and maintain equipment, interpret system performance, and make operational decisions regarding configuration and source selection. From personal interactions, we know that crews are eager to learn, share knowledge with each other, and be effective navigators. In that sense, little has changed since the days of Nathaniel Bowditch.

CONCLUSION

Today, sailors have an array of amazing technology to exploit for safe and accurate navigation. Emerging challenges awaken us to the reality that navigation is not a solved problem. A resilient navigation system can overcome these challenges by offering a diverse selection of sensors, effective sensor integration, navigation sensor integrity monitoring and alerting, and effective operator training. The importance of navigation in meeting a ship's numerous mission objectives is as critical today as it was for Nathaniel Bowditch, and modern navigation systems must meet the current challenges and anticipate future ones.

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