ISSN 2075-1087, Gyroscopy and Navigation, 2024, Vol. 15, No.1, pp. 84-101
Russian Text © The Author(s), 2024, published in Giroskopiya i Navigatsiya, 2024, No. 1, pp.115-142

Navigation without GPS

B.S. Rivkin

Concern CSRI Elektropribor, JSC, St. Petersburg, Russia
e-mail: brivkinel@mail.ru

Received February 6, 2024; reviewed March 14, 2024; accepted April 10, 2024

Abstract: The article focuses on the problems of GPS application and offers an overview of different GPS backup technologies and approaches proposed in the United States, the European Union, UK, China and some other countries to overcome its shortcomings. Also considered are some well-known PNT services using low Earth orbits (LEO) satellite signals, eLoran radio navigation system, as well as some exotic approaches.

Keywords: Positioning, Navigation and Timing (PNT), low Earth orbits (LEO), eLoran, signals of opportunity, R-mode, muon technology.

1. INTRODUCTION

In the second half of 2023, an extensive program was organized in the USA to celebrate the 50th anniversary of gaining approval for the full-scale GPS demonstration. One of the most interesting events was the presentation made by the 88-year-old Brad Parkinson, the recognized father of GPS during the 17th Annual PNT Symposium at the Stanford University [1].

Parkinson recollected that GPS development was preceded by the US Air Force studies completed in 1966, during which a broad range of spacecraft navigation methods were considered. The hardest of the 12 alternatives was selected. Numerous talented engineers contributed to realizing this idea, and Parkinson gave many of them credit during his talk, including Malcolm Currie, whom he called the GPS Godfather.

When Parkinson went to the Pentagon in 1973 to put forward a GPS plan to the Defense Systems Acquisition Review Council (DSARC), it was Currie who was at the table of admirals and generals who rejected it. He talked with Parkinson after the meeting and told him the current design was not optimal, but with a redesign, it had a good chance of gaining approval. To make it happen, about 12 people gathered in the Pentagon over Labor Day weekend. They confirmed the modified concept of the system, which first used four satellites, but proposed to switch to a new modulation scheme. The space hardened clocks and code division multiple access (CDMA) signals were also added over that weekend. Now, 50 years later, they are being introduced in the Russian GLONASS. The greatest roles in GPS development, according to Parkinson, were played by the great engineering talents Gaylord Green, Steve Gilbert, and Mel Birnbaum.

When the festivities were over, everything returned to normal, and the GPS users faced the major challenges in the system application: banal signal jamming and much more sophisticated spoofing, when the real system signal is substituted with a fake copy causing the receiver to incorrectly determine its position.

Low noise immunity of GPS signals is due to their low power: 50 W for L1 and 8 W for L2 signals. For comparison, the European GNSS Galileo, whose development was started in 1994, some 20 years later than GPS, had 1600 W signals.

Obviously, the other GNSS systems — Galileo, BeiDou and GLONASS — are also susceptible to spoofing. However, due to the fact mentioned above and the huge number of GPS users throughout the world, which greatly outnumbers the number of other GNSS users, the English technical publications actually focus on GPS noise immunity only. This was the reason why here I concentrate specifically on GPS problems, which is reflected in the title of this article, and cover mostly foreign publications. The readers interested in the approaches to GNSS-free positioning developed in Russia are referred to the article by V.G. Peshekhonov, Academician of the Russian Academy of Sciences [59].

Professor David Last, who once said that the GPS signal is like a car headlight 20 000 kilometers away, describes an experiment the results of which are explained by the low power of the emitted signals [2]. A milliwatt jammer was installed on board the Galatea research vessel and turned on, which caused false GPS positions, the autopilot steered the ship off the set course, and automatic identification system (AIS) broadcasted false ship motion parameters. Today, the Internet advertises a much more powerful device that costs only £101 and is capable of jamming all GPS and Galileo signals. It is noteworthy, said D. Last, that a detector installed close to a regional British airport gets up to 200 jamming hits a month.

Actually, as far back as in 1997 at the Aviation Salon in Moscow [3] it was demonstrated that the most primitive 4W jammer can jam the GPS signals within 200 km. As the years passed, it got worse. In 2010 the car thieves started to use the transmitters for jamming GPS signals in order to paralyze the satellite car tracking systems, and two years later, the greatest jamming attack happened near the South Korea coasts, when the crews of 553 planes from two largest airports of the country and hundreds of ships reported GPS failure.

Spoofing, which introduces the intended interference in the pseudoranges to the satellite, makes it possible to bring an AUV navigated by GPS receiver to any desired point. A research by Bjorn Bergman from a nonprofit organization SkyTruth contains interesting data on spoofing: ships in various parts of the world were found reporting GPS locations thousands of miles away [4]. For example, the Beagle moored near the California coast in February 2019 was positioned by GPS to be near Bergen (Norway) for 37 h, and the Princess Janice located at the same place in June 2019 turned out be close to Nigerian coast for 392 h.

Recently, the navigators have started to face a challenge never seen before. All the trade ships are equipped with AIS transponders, which, among others, broadcast their GNSS positions to other ships in the area. As a result, the crew of a ship moving near Shanghai along Yangtze can view the following image (Fig. 1) when displaying AIS data of a neighbor ship on ECDIS screen [5].

The ship, which is currently at one point, starts moving in a circle at a speed of 21–31 kn according to GPS information under the influence of spoofing. The specialists are more mystified by the sophisticated technique creating this fantastic image rather than by the fact of spoofing in this area.

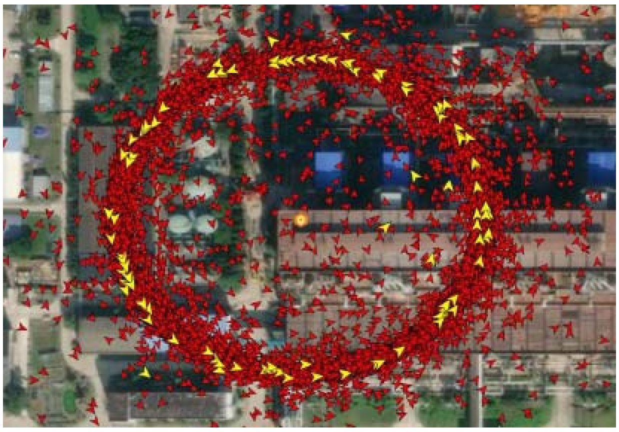


Fig. 1. Virtual path of an anchored ship due to spoofing

Analyzing the situation, it becomes clear that spoofing is the first problem to be combatted, because its effect, unlike the traditional jamming, is much more difficult to detect. Up to date, there is no effective spoofing protection methods for receivers. In principle, it is possible to include an adaptive phased antenna array into the receiver in order to create a directional pattern that actually removes the interference from the directions inconsistent with the satellite position in the sky; however, it is not likely to be implemented in commercial equipment. As to the problem in general, it was covered in the report by the European Global Navigation Satellite Systems Agency containing information on 18 months of observations in 2016–2017. According to the Agency, during this time more than 160 000 GNSS failures were detected in 14 countries of the European Union. The report does not specify which failures should be attributed to technical malfunctions, and which, to external interference, including spoofing.

This situation naturally worries those in charge of navigation of vehicles, both in civil transportation and defense technology. Using GPS-free technologies in military applications has become a paradigm for Defense Advanced Research Project Agency (DARPA). “Position, navigation and timing (PNT) are as essential as oxygen for our military operators”, DARPA Director Arati Prabhakar said back in 2012 [6]. “Now we are putting new physics, new devices and new algorithms on the job so our people and our systems can break free of their reliance on GPS”.

A slightly different approach to the development of a backup system, preferably of the same accuracy as GPS, is discussed in [7]. Resilient PNT is a key condition for the introduction of e-Navigation concept put forward by IMO, which requires, among the others, that two independent dissimilar and nearly equal-accuracy PNT systems be available on board the ship. The IMO Resolution A.1046(27) imposed the requirements on PNT performance and specified that the PNT systems should be selected based on their vulnerability to interference, natural or intentional. For civil ships, the Resolution requirements for the positioning error in the coastal navigation (max 10 m in 95%) and the signal availability are fulfilled in 99.8% with joint application of GPS and GLONASS (when used alone, none of the systems meets the availability requirement), whereas the noise immunity is not provided with any GNSS combinations.

So far, when speaking about GPS vulnerability, we have concentrated on jamming and spoofing. However, the environment provides a significant unintentional effect on the receivers, which is outside the scope of this paper. For the major aspects of this problem, see [60].

We cannot but mention that the vulnerability of GPS and any other GNSS can partly be compensated by integration of the GPS receiver with an inertial navigation system, depending on the situation and the developer's talent. However, the abundance of literature devoted to this problem requires a separate article.

Below we discuss the GPS backup technologies based on the same satellite measurements, using eLoran radio navigation, and the new approaches, sometimes rather exotic.

2. SATELLITE TECHNOLOGY

All the ongoing work concerned with PNT data provision based on the satellite measurements instead of GPS signals is focused on the idea of placing satellites not in medium Earth orbit (MEO), but in LEO, wherein the signals received on the Earth are many times stronger as compared with those of the GPS. The examples are Transit (USA), the first satellite navigation system put into operation in 1964 and the first Soviet satellite navigation system Tsiklon (Cyclone) (its civilian version is known as Cicada), which was put into service in 1976.

1. Among the first to start developing this idea were Orolia and Satelles (both the USA). In December, 2016, the companies announced a strategic alliance aimed to develop PNT technology based on the Iridium satellite constellation, independent of GPS/GNSS signals [8]. Towards this end, Satelles' satellite time and location (STL) signal technology was supposed to be used to provide for positioning and timing data independent from traditional GPS and other GNSS satellite signals. STL signals transmitted by Iridium low-orbit satellites are up to 1000 times stronger than those of any GNSS, which prevents jamming. In addition, this technology ensures STL-signal reception inside buildings and GNSS-denied environments. It is also significant that STL signals are encrypted.

The following characteristics were supposed to be achieved (data for GPS are given in brackets) [16]:

– timing error – 200 ns (20 ns);

– positioning error – 30–50 m (3 m);

– time to first fix – 10 min (100 s);

– anti-spoofing is provided by encrypted signal (unavailable for civilian customers);

– the fight against signal jamming is ensured due to signal power (not provided).

Later it was reported that both of these companies became part of the Open PNT Industry Alliance, which also includes Iridium Communications, infiniDome, Jackson Labs Technologies, NAVSYS Corporation, NextNav, OPNT, Qulsar and Seven Solutions [17].

The Alliance aims to support US effort in implementing backup PNT systems that do not rely on GNSS signals, for critical infrastructures, which include transportation systems, communications networks, energy generation and distribution platforms, as well as financial services structures.

2. Noteworthy is the fact that it is also possible to create your own satellite navigation system without caring about launches of any kind of spacecraft [9]. Zak Kassas, an electrical engineer at Ohio State University, Columbus, spoke about this at the annual GNSS conference in St. Louis, USA. Initially, he and his colleagues used the satellite signals from the communications companies Orbcomm and Iridium Communications to solve navigation problems. Later, they moved on to Starlink. Using their own small receiver and software, Kassas and his team picked up the signals from six Starlink satellites flying overhead on different trajectories, which allowed them to fix the location of a stationary observer on the ground to within 7 to 8 meters error. Given the more than thousand-fold superiority in power of the Starlink satellite signal in LEO orbit compared to GPS signals, it is possible to solve the positioning problem in conditions where GPS signals are unavailable, for example, under the forest canopy.

Let us see how the idea of using LEO positioning in different locations is coming to life.

European Union

1. In 2018, Francis Soualle, Airbus, France, speaking at the International Symposium in Toulouse, drew attention of the participants to the renaissance of interest for large LEO systems and space infrastructures using cheaper and smaller satellites, so-called mega-constellations comprising hundreds of satellites and nanosatellites that provide global coverage [10] These primarily include OneWeb satellite constellation (720 satellites, ensuring the reception of signals from 30 to 90 satellites with a minimum elevation angle of 5°), Telesat (117 satellites, from 8 to 10 satellites in the same conditions) and Starlink (4425, from 150 to 300, correspondingly). The data are valid for 2021.

In his report, the author presents the following information:

such a system has high stability of HDOP, the so-called "geometric factor", which significantly affects the positioning accuracy. For example, if an object is located at the equator and it processes data from a satellite with a minimum elevation angle of 5°, then over a 2-h interval of observations, the HDOP value for Galileo GNSS will vary in the range of 0.9–1.5, whereas for OneWeb, it will be constant and equal to 0.35. The significance of this parameter follows from the fact that the error in determining plane coordinates using any GNSS is given by the relation

$\Delta = \text{UERE} \times \text{HDOP}$, where UERE is a user equivalent range error, characterizing the instrumental error of the system, HDOP is a factor of horizontal dilution of precision;

(2) HDOP value for Galileo, depending on the observer's latitude and the time of day, varies in the range of 0.9–1.5, while for OneWeb, for example, it is in the range 0.25–0.40;

(3) for systems with a mega-constellation, it is possible to switch to the Doppler algorithm for the positioning problem solution with an error (under certain conditions) of several meters.

2. In November 2022, at a meeting of the Council of the European Union, the European Space Agency (ESA) requested several hundred million euros for new satellite navigation technologies on low Earth orbit and the Moon [11].

ESA officials said they are going to spend about 500 million euros ($518 million) over the next three years on projects to develop advanced technologies. The initiative, called FutureNAV, will be supporting the development of two missions to advance satellite navigation technologies. One of them, Genesis, involves launching a satellite into a 6000-km orbit aimed to improve the international terrestrial reference frame with an accuracy of up to 1 mm, and to precisely determine the orbits of the Galileo satellites, which will also radically improve the accuracy of positioning using signals from this GNSS.

The other project, LEO-PNT, which is expected to cost 100 million euros, aims to create a small satellite navigation constellation in low Earth orbit, including from 6 to 12 small satellites. The satellites of this system will be in orbit just 222 km from the Earth, complementing the satellites of the European Galileo, which are 23 222 km away from the Earth. Operating from LEO, the satellites will provide stronger signals and greater resistance to jamming, particularly due to the use of frequency bands other than those used in GNSS. By bringing satellite navigation closer to Earth, LEO-PNT could make satellites cheaper and more efficient, and launches more cost-effective.

ESA's plan [12] is, first, to launch a mini-constellation to test key technologies and demonstrate signals and frequency bands to be used by a subsequent operational constellation, in the same way that the European GIOVE test satellites paved the way for Galileo. Each individual satellite will be relatively small, weighing less than 70 kg, compared to a 700 kg current Galileo operational satellite. It is assumed that by using time signals transmitted from Galileo satellites, it will be possible to dispense with precision atomic standards in spacecraft equipment.

LEO-PNT, ESA officials said, aims to be a "fast-track" demonstration project that would launch small satellites in 2026 to demonstrate the potential capabilities of such a constellation. This would facilitate future planning for the development of a LEO navigation constellation, including whether it would use autonomous satellites or payloads placed on existing LEO-orbiting satellites.

The UK

One of the consequences of Brexit for the UK was that it was excluded from the European pool that owned Galileo and had to solve the GPS problem relying on its own resources. Recently, the idea of creating a national system using OneWeb, the British startup company, whose satellites operate on a frequency different from GPS and Galileo and are placed in a lower orbit, which provides a stronger signal than is available with the GPS, is receiving increasing support [13]. In this case, the cost of the system shall not exceed £1 billion. However, in March 2020, OneWeb filed for bankruptcy, reportedly due to problems caused by the pandemic. It is currently unclear who will be financing such an expensive project as the creation of global broadband Internet. At the same time, there is information that the US Department of Defense is considering investing in OneWeb, if only to prevent its satellites and 44 ground stations from being bought by the Chinese.

Nevertheless [14], as reported by The Daily Telegraph, the OneWeb company officials say they are ready for cooperation, which would be possible if the second generation of its satellites is put into orbit. As Chris McLaughlin, the OneWeb spokesman responsible for the company’s interaction with government agencies, stated it had always been understood that the first generation would not be able to fully provide PNT services, however, as the OneWeb constellation evolves and is replenished with its second generation, the OneWeb global satellite constellation will be well on its way to delivering a reliable system.

The British government is considering various possibilities for cooperation with OneWeb. One of them suggests that its low-orbit satellites will be used to duplicate signals from the American GPS and European Galileo in order to provide additional protection against the outside interference with navigation systems. A commission that produced a report on these problems for the British government in 2017 estimated that the damage to the UK economy from a massive GPS failure would be as high as $1.4 billion per day.

China

The creation of another satellite system by the China Aerospace Science and Technology Corporation is reported in [15]. The Hongyan LEO communication system is based on 60 small spacecraft placed in LEO orbits. It is intended primarily to provide for global communications and supply global consumers with various information services.

The authors propose to use Hongyan for the tasks traditionally assigned to the Satellite Based Augmentation System (SBAS) intended to improve the efficiency of GNSS operation. The satellites of the Hongyan system are supposed to be launched into 5 900-km circular orbits, evenly spaced relative to the Earth, with 10 operating satellites and 2 reserve ones positioned equidistantly on each of the orbits (see Fig. 2). The ground sector of the system consists of reference and processing stations, as well as a network of data transmission stations.

The principle of the system operation aimed to solve the tasks assigned to SBAS is described below (the problems of data transmission to consumers for calculation of ionospheric delays are not discussed in this paper). The receivers installed on the Hongyan satellites monitor the signals from GNSS satellites, transmitting the relevant data via intersatellite links to the central processing station. The latter uses these data and information supplied by ground reference stations to produce clock corrections and refine the orbital parameters of GNSS satellites, which are eventually broadcast to consumers. It is expected that, based on these data and standard GNSS phase measurements, it will be possible to provide precise point positioning (PPP) of the consumer in dynamics with an error in the subdecimeter range and in statics, in the subcentimeter range. In this case, the time before the first PPP solution is obtained does not exceed 5 min (for the existing SBAS, this time ranges from 30 min to 1 h).

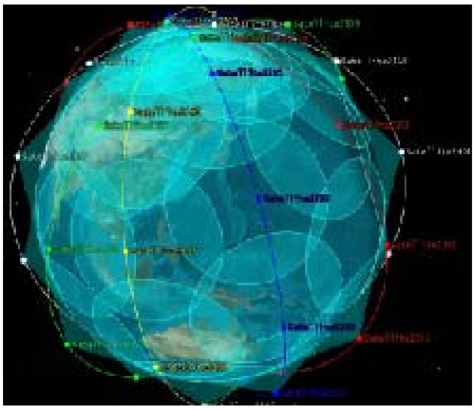


Fig. 2. Architecture of the Hongyan satellite system

In order to estimate the efficiency of the proposed option for the Hongyan satellites, the paper presents the simulation results, wherein the BeiDou system was considered as a GNSS. This involved measurements from 8 reference stations in China and sequentially data from three and ten Hongyan satellites.

Also, the authors studied HDOP. Thus, in Xi’an, where the HDOP for the BeiDou system was on average 2.32 per 24 h; the use of LEO data reduces this value to 2.09. The greatest benefit from the Hongyan satellites in terms of HDOP is observed in the circumpolar regions.

Finally, it is emphasized that special services for military applications will be created on the basis of the Hongyan data to improve the efficiency of using GNSS in rugged terrain and complicated interference environment.

The United States

1. The United States is financing a number of projects that use signals from LEO satellites. Among the first to start up in 2017–2018 was DARPA's program aimed to create the Blackjack navigation satellite system in low orbits. With this purpose in view, DARPA allocated \$13.3 million to Northrop Grumman in 2019 [18]. It was assumed that that amount of money would be sufficient to develop a preliminary design of the system and the first version of the payload for its satellites, while the first spacecraft was planned to be launched in 2021.

Although the development is carried out primarily in the interests of the US Department of Defense, the developers of the system intend to develop its commercial sector as well, including provision of broadband Internet to consumers. At the same time, as stated by Northrop Grumman Vice President Nicholas Paraskevopoulos, for military consumers, Blackjack will broadcast a frequency-agile navigation signal, independent of existing GNSS. Of critical importance for the preliminary project is to confirm the fact that, in terms of its accuracy characteristics, Blackjack will not be inferior to the existing GNSS, while the launch cost of one satellite of the system into orbit will not exceed \$6 million.

However, obviously, the project has stalled; moreover, the main contractor was changed, as evidenced by the fact that in April 2020, DARPA allocated \$5.8 million to Lockheed Martin [19]. Based on the latest data, the first Blackjack satellites may be expected to be launched in 2024.

2. Similar technologies based on small LEO satellites are expected to be used by the US Army to provide support to their ground forces. Previously, in 2017–2018, they had experience in using the observation microsatellite Kestrel Eye [20]. In this regard, three development programs called Gunsmoke, Lonestar and Polaris will be initiated over the next few years, their objective being demonstration of PNT capabilities in LEO to provide support in ground combat operations.

Gunsmoke has been underway since November 2018, when the Army awarded a two-year \$8.3 million contract to Dynetics, based in Huntsville, Alabama, to develop, test, integrate, and demonstrate two tactical spacecraft to support ground troops.

3. Another LEO constellation is patronized by the US Space Development Agency (SDA), subordinate to the office of the Undersecretary of Defense for Research and Engineering Mike Griffin [21, 25]. This system will be based on several hundred small-sized spacecraft. The cost of their manufacturing and launching into orbit will be immeasurably less as compared to that of the GPS satellites.

All satellites in this system will incorporate intersatellite optical links making it possible to exchange the data on the time scale of each satellite and determine their relative position, so that the system will be able to function practically independently of its ground segment.

The main purpose of the system is to determine the coordinates of ground and sea targets, as well as to detect launches and provide tracking data for hypersonic vehicles and the latest generations of missiles. The PNT capabilities are assigned to the satellites of the so-called Transport Layer, which will initially comprise up to 150 satellites. The first 20 of them are already being manufactured by Lockheed Martin and York Space Systems as part of Tranche 0. They are supposed to be put into 1000-km orbits in two launches.

Tranche T0 satellites are not supposed to deliver information to the warfighters, but only to test primarily inter-satellite laser crosslinks. On obtaining positive results of this work, it will be possible to proceed with creation of Tranche T1 satellites. SDA is now seeking up to three contractors to manufacture another 144 spacecraft to be placed in 6 orbital planes in 2024.

Full deployment of the system is expected to be completed in 2028 with the launch of Tranche T3 satellites, providing the necessary information to the above-mentioned warfighters anywhere in the world.

4. Xona Space Systems, a startup founded only in 2019, has been getting close attention recently. Yet, in the foreseeable future, it plans to place 300 of its own navigation CubeSats in LEO orbits [22]. Surprisingly, the Xona developers announce the positioning error of the navigation system they are creating an order of magnitude smaller than that of standard GPS, which was indirectly confirmed during ground-based experiments. The transmission of information to consumers will be carried out using an encrypted signal.

In May 2022, Xona launched a test satellite into LEO orbit as part of Elon Musk's Transporter 5 mission to demonstrate the capabilities of high-precision PNT [23]. This project was supported by Hexagon/NovAtel (Sweden/Canada), which contracted to develop a receiver for the PULSAR navigation satellite system being developed by Xona. Since the spacecraft of this system will be located much closer to the Earth than the GPS spacecraft, the signals they transmit will be immeasurably more powerful than the GPS signals, providing a significant level of noise immunity from external effects, which will potentially lead to increased positioning accuracy due to the rapidly changing geometry in LEO systems.

PULSAR will transmit encrypted signals on two frequencies, ensuring their authentication. Advanced Encryption Standard—a symmetric block encryption algorithm—will be used for PNT data transmission, and for authentication, Elliptic Curve Digital Signature Algorithm—a cryptography scheme based on elliptic curves.

Xona's immediate plans were shared by Tyler Reid, Chief Technical Officer of Xona Space Systems. First of all, they are concerned with the Huggin mission. It is within its framework that signals will be transmitted in the L and C bands, providing consumers with navigation data, including corrections to GNSS measurements. It is expected that with at least one satellite in LEO orbit, the system will be able to halve the time to obtain the first PPP solution due to its rapidly changing geometry.

However, Reid noted that a major drawback of the LEO system is the need to launch about 10 times as many satellites as there are in MEO in order to provide comparable coverage and HDOP. Another disadvantage is that the satellites will be located lower above the horizon, which will also reduce the efficiency of the LEO system.

5. Extremely interesting research is being conducted by the group headed by Todd Humphreys, who suggested that Elon Musk use his Starlink megaconstellation for navigation. "No, thank you!" Musk replied. Researchers went ahead anyway [24]. With a few software tweaks, they say, the rapidly growing Starlink constellation can provide PNT. This idea is perfectly in line with the US Army, which is funding Humphreys' research at the University of Texas at Austin (UT Austin) in hopes of getting a backup to its vulnerable GPS system. Can Starlink fulfill that role?

When the idea was first proposed in 2020, SpaceX executives were open to it. Then a directive came from above. Musk explained that every other LEO communications network, like Starlink, had gone into bankruptcy, therefore, SpaceX has to fully focus on staying out of it.

Humphreys claims to have provided the most complete characterization of Starlink signals to date. This information, he said, is the first step towards developing a new global navigation technology that will work independently of GPS or its European, Russian, and Chinese equivalents. "The Starlink system signal is a closely guarded secret," says Humphreys. "Even in our early discussions, when SpaceX was being more cooperative, they didn't reveal any of the signal structure to us. We had to start from scratch, building basically a little radio telescope to eavesdrop on their signals." To launch the project, UT Austin acquired a Starlink terminal and used it to stream high-definition tennis videos from YouTube. The terminal provided them with a constant source of Starlink signals that a different nearby antenna could eavesdrop.This provided a constant source of Starlink signals that a nearby antenna could listen to.

Humphreys quickly realized that Starlink relied on a technology called Orthogonal frequency-division multiplexing (OFDM). OFDM is an encoding digital transmission method originally developed at Bell Labs in the 1960s and currently used in Wi-Fi and 5G, allowing the largest number of bits per second to be packed into a specified bandwidth. Austin researchers did not try to break Starlink's encryption or access any user data coming from the satellites. Instead, they sought out synchronization sequences—predictable, repeating signals transmitted by satellites in orbit to help receivers coordinate with them. Each sequence also contains clues about the distance to the satellite and its velocity. If the ground receiver has a good idea of the satellites movements that SpaceX shares online to reduce the risk of orbital collisions, it can use the regularity of the sequences to determine which satellite they came from and then calculate the distance to that satellite. By repeating this process for multiple satellites, a receiver can locate itself to within about 30 meters, says Humphreys.

If SpaceX decided to cooperate by including additional data on each satellite's exact position in the Starlink transmitted data, that accuracy could theoretically improve to less than a meter, making it competitive with GPS.

A fuller understanding of Starlink's signals has consequences going beyond navigation. For instance, the system's satellites currently do not seem to be using two of the eight channels for which SpaceX is licensed. Humphreys speculates that this could be because Musk is keen not to interfere with radio telescopes operating at neighboring frequencies. The bright streaks of orbiting Starlink satellites have already been accused of disrupting astronomical observations. The UT Austin findings also highlight the possibility of deliberate tampering with Starlink itself. Humphreys notes that while timing sequences are promising for navigation, the fact that they are completely predictable and used across an entire constellation is a security vulnerability. However, it should be taken into account that any navigation system that works with open-source sequences can definitely be spoofed, because everyone will know how to detect these signals and imitate them.

3. eLORAN RADIO NAVIGATION SYSTEM

According to an increasingly popular opinion, eLoran is the only system actually able to provide PNT services with the performance close to GPS. One of the eLoran advantages is that no effective interference to its signals can be created. This is due to the fact that the GPS signal emitted in the GHz range has a power of 50 W, whereas eLoran works at 100 kHz and emits 250 kW signals.

eLoran provides the GPS positioning accuracy in differential mode, which was confirmed as far back as in 2014: the positioning error does not exceed 10 m with 0.95 probability [26].

The tests performed in January 2017 by UrsaNav (USA), the eLoran developer, to check the UTC determination demonstrated that [27]:

- 95% of all measurements were within 156 ns of UTC;
- without differential corrections, the errors were max 172 ns at distances up to 800 miles from the transmitter, and with differential corrections, max 15 ns.

What is the situation with eLoran deployment in different areas of the World Ocean?

The United States

In December 2015, the US Department of Transportation (DoT) posted a document DOT-OST-2015-0105 in which it outlined its intention to shut down 62 Nationwide Differential GPS (NDGPS) stations [28]. DoT explained its decision by the fact that it intends to create the national eLoran-based PNT system, the principled position on which as a resilient GPS backup was adopted by the US Government in 2008 and confirmed in 2014. Only the interference of a number of US Congressmen, who declared that this plan should not be implemented until a final conclusion on the eLoran system was adopted, put its implementation on hold.

What happened further confirmed that that was a right choice, because no specific steps on eLoran implementation were made by US administration. Moreover (see [29]), after the US administration took a decision to stop using Loran-C in 2010, only eight of 25 Loran-C stations in the USA to be upgraded to eLoran retained their transmission towers, not to mention the commonly removed generators, transformers, and other facilities. At the same time, as noted in [30], Russia, China, Iran, Saudi Arabia, and South Korea have Loran-C like systems to protect their infrastructure in the event of local or global disruption of GNSS signals.

In connection with this, the US House of Representatives Act H.R. 2825 of July 2017 is of great interest. Its Chapter 807, *Position, Navigation, and Timing,* states the need to establish eLoran in the USA. The system shall meet the following major requirements:

– ensure the availability of uncorrupted PNT signals for military and civilian users in the event that GPS signals fail to meet the system requirements;
– be terrestrial, provide wide-band coverage, and transmit wireless signals;
– transmit a precise, high-power signal in the 100 kHz spectrum and meet the one microsecond UTC accuracy requirement;
– be able to penetrate underground and inside buildings.

Europe

1. Stringent accuracy requirements comparable to GNSS requirements need to be met for eLoran application in coastal navigation and harbor entrance. The feasibility of meeting these requirements is analyzed in [31].

Obviously, eLoran positioning error for a certain Earth region can be predicted only using the adequate error model. The influence of the following two delays in radio signal propagation is analyzed in the publication mentioned above:

- primary factor (PF) delay caused by atmospheric effects;
- additional secondary factor (ASF) delay caused by the deviation of radio wave propagation phase velocity from the accepted value and connected with the signal passage over Earth areas.

Previously, in Loran-C, the effect of PF delays was compensated with the Brunavs model; however, there was no relevant model for eLoran. The paper proposed an improved empirical error model that takes into account both ASF and PF delays.

This model was used to estimate the system error for the European region. According to the results, eLoran can achieve a max 20 m error in the North Sea and a 10 m error in some European ports, however, in Ireland it increases up to 80 m and can be reduced to 10–20 m required by IMO by including at least two eLoran stations in this region.

2. A large paper in *Inside GNSS*, June 2017 [30] is devoted to eLoran development in Europe (note that the journal focuses on satellite technologies, however, here it finds a place for an article on radionavigation system).

To begin with, unlike the USA, all Loran-C chains in Europe (one each in the UK, Germany, and Denmark, two in France, and three of the four in Norway) are “in good health”. They are not used, but can be revived any time. Moreover [32], the UK activated eLoran stations in Dover and Harwich, which provided navigation near the eastern coast, back in October 2014. By 2020, five more stations had started working, which ceased the need in GPS signals in the North Sea and Atlantic Ocean areas near the UK.

Since 2015, the UK, a leader in promoting eLoran, has been conducting a research at the Anthorn Radio Station. David Last, the former President of the Royal Institute of Navigation, informed *Inside GNSS* that “It’s delivering, certainly, a microsecond. We are aiming for 100 nanoseconds service in due course and that will require a differential operation – but the substantial market is for a microsecond at the moment”. This is due to the fact that eLoran hardware, just like GNSS satellite hardware, includes three atomic clocks.

3. As has already been mentioned above, eLoran positioning error should not exceed 10 m. However, the marine pilots working near Rotterdam, the largest river port in the world (the length of its quay walls is 45 km), consider these requirements insufficient. An innovative decision in creating differential eLoran was proposed by Reelektronika (the Netherlands), with the results reported by the company leader Durk van Willingen in [33]. The research conducted by Reelektronika has shown that eLoran errors in differential mode are mostly due to:

– deviation in the transmission of corrections through Eurofix, reaching 15 min, which makes them outdated;

– ASF errors.

The problem is that there is no ASF model adequate to the atmospheric condition and underlying surface (sand, stony land, etc.) yet, and to exclude its effect on the result, the ASF should be measured accurate to several nanoseconds, which is practically unattainable.

Based on these findings, Reelektronika developed an original eDLoran infrastructure including a series of reference stations and a server, which simultaneously acts as a system control center. The user is then assumed to have a Loran-C receiver (and therefore, the system transmitting stations need not be upgraded to eLoran requirements) with the original software. Connection between all the system users is implemented via a standard GSM channel (the reference stations may be also connected to the server through the Internet), which reduced the delays in sending the differential corrections to 2 s.

The developers also followed the original path in combatting the ASF. In their system version, the user coarse Loran-C positions are transmitted to the system server for joint processing with the data from the reference stations. Integrated processing allows identifying the error introduced by ASF into the coarse positions, and relevant coordinate corrections are sent to the user rather than the ASF corrections traditionally introduced in pseudoranges, the accuracy of which was discussed above.

The tests in Rotterdam area using the signals of Loran-C transmitting stations in Lessay (France), Sylt (Germany), and Anthorn (the UK) revealed that the positioning error even for a moving vessel using Reelektronika equipment in 95% does not exceed 5 m, which meets the pilotage requirements in this region.

South Korea

1. It was stated earlier that GPS signals practically cannot be used in the most part of South Korea, because they are effectively jammed by its northern neighbor. For this reason, first of all, South Korean

specialists plan to deploy a network of five eLoran base stations and 43 differential stations in the coming years in order to provide navigation service in this region of Southeast Asia [34].

2. In this regard, the results obtained by the South Korean developers on positioning using the standard Loran-C system equipment operating in a special mode are interesting. As is known, the Loran-C positioning algorithm is based on hyperbolic navigation relying on the time difference of arrival (TDOA) of signals from various transmitting stations of the system chain, one of which is the master, and the rest are slaves. The measurements are synchronized only within this chain; therefore, TDOAs of various chains cannot be used in the standard version.

This limitation was removed in [35], where an original algorithm was developed for processing TDOA obtained by multichain positioning. The algorithm was tested for positioning of a stationary vehicle with simultaneous accounting for radio signal time delays.

While PF and SF delays, where SF are the secondary factor delays occurring when a signal passes over the sea surface, are easily compensated with the Brunavs model in Loran-C receiver, ASF delays need special measures to be compensated. In the case under consideration, since the object was stationary, it was sufficient to use a single time-varying ASF value generated by the correction station working in the differential mode (dLoran). As a result of this experiment, the positioning error of max 15 m in 95% was achieved over a 21h observation interval.

The algorithm modification for a moving object including the generation of ASF map for a test area is considered in [36]. An integrated GPS/Loran-C receiver (GPS channel used as a reference) was installed on board a car moving on a 4.5 km long highway at 60 km/h.

At the first step, the signals from one Loran-C chain were used for positioning with the standard algorithm, with the error being max 87 m in 95%. With the application of the second chain, the signals from which were available at the test area, the error was decreased to 37 m.

Surely, these are not units of meters provided by GNSS and even not 10 m promised during the eLoran deployment, nevertheless, it is a decent result. Moreover, it should be taken into account that the results were obtained in terrestrial tests, where ASF provide a maximum effect. In marine applications, the positioning errors are naturally expected to be much lower.

3. The real eLoran performance is also addressed in the paper “Analysis of Positioning Performance to Meet HEA Requirement in eLoran Testbed” by K. Seo, S. Park, T. Fang, and S. Lee, South Korea, presented at the 16th Congress of International Association of Institutes of Navigation in November 2018.

The authors intended to check if eLoran was able to provide harbor entrance and approach (HEA) positioning error of 10 m required by IMO [62]. At the first step, eLoran solution was simulated using signals from Loran-C stations in Pohang, Gwangju, and temporal station in Incheon. The simulation showed that only a 20 m error could be guaranteed.

At the second step, a multichain solution was simulated, using the signals not only from Pohang and Gwangju stations, but also from five more Loran-C stations in the chains in China and the Russian Federation (in Ussuriysk). However, even in this case, a 10 m error was achieved only at the sites with low HDOP and the relevant position lines intersected at almost right angles.

South Korea relies on eLoran: The Ministry of Oceans and Fisheries declared this system to be the core technology of the fourth industrial revolution and the key next-generation PNT technology for the Navy [37].

The system is expected to become operational in the coming years. Two existing Loran-C stations will be upgraded to meet eLoran requirements, and a new transmitting station will be put into operation (two differential correction stations have already been commissioned and are being tested). To this end, a contract was signed with the UrsaNav office in Billerica, USA, covering the supply of a new station in Incheon and the development of an integrated GPS/eLoran receiver. The receiver prototype was tested under GPS signal jamming and spoofing, with the results confirming the high positioning quality, whereas the standard GPS receiver failed to provide positioning in these conditions.

The South Korean government plans to achieve a max 20 m positioning error at max 30 km from the differential reference stations with eLoran. China is also conducting similar research, planning to install three more eLoran transmitting stations in the western part of the country [38].

4. NEW TRENDS

1. In recent years, the United States have undertaken numerous actions with a view to provide backup for the GPS [39]:

- in 2015, demolition of Loran-C infrastructure was halted pending a decision on a GPS backup system;
- in 2016, The National Defense Authorization Act was adopted directing the Departments of Defense, Homeland Security and Transportation to submit consistent requirements for a domestic GPS backup and report before the end of 2017;
- in 2017, $10 million was allocated for the development of a plan for a GPS backup technology demonstration by April 2018 and completion of the project by June 2019;
- in 2018, a total of $20 million was committed in three tranches (March, August and September) for GPS backup technology demonstrations, which were to be conducted by the end of 2018, but were not completed;
- in December 2018, the directive was passed, which obliged the Secretary of Transportation to establish a terrestrial GPS backup system by the end of 2020, which must be difficult-to-disrupt, wireless, synchronized to UTC, capable of penetrating inside buildings and underground, and compatible with the operation of similar systems, for instance, eLoran [40].

It is emphasized that the forthcoming system must provide not only positioning and navigation of mobile objects, but also accessibility to a fault-tolerant and nondegrading time signal in the situations of the GPS navigation signal outages.

Decisive measures to prevent jamming and spoofing were taken by the US Department of Transportation in 2019, which allocated $2.5 million to US companies to develop technologies that provide GPS-independent PNT services. Moreover, it selected 11 companies to develop and demonstrate technologies that could be used to back up the services provided by GPS, should GPS signals be jammed, spoofed or unavailable, and announced that the number of such firms might be expanded to 20 [41].

The demonstration of results with simulated external effects was expected to take place in the first half of 2020. It was assumed that the developed system would solve at least one of the tasks (generation of precise time or positioning) with an error commensurate with the GPS characteristic. What did those 11 companies count on [42]?

PhasorLab was searching for a solution based on a ground analog of GPS, capable of maintaining high-precision time (<<1 ns) and frequency (<<1 ppb) synchronization throughout the whole network, with the stationary nodes referenced to a 3D map for a given area. There was also an option with a mobile network.

Skyhook Technology relied on its immense database that contained 5 billion geolocated Wi-Fi access points and 200 million cell base station IDs, thus making it possible to accurately locate various gadgets worldwide.

Hellen Systems based its solutions on advanced eLoran technologies. They intended to develop a solid-state eLoran transmitter integrated with advanced timing and frequency products from Microsemi. Some other companies, in particular, UrsaNav and Serco were also going to use eLoran signals to some extent in their technologies.

Globalstar-Echo Ridge, as the name of the company already implies, relied on Augmented Positioning System technology that uses ordinary signals from the Globalstar communications satellites (a constellation of 24 LEO satellites) rather than from navigation signals.

Satelles followed a similar path, using signals from the Iridium system of 66 LEO satellites. Unlike GPS, its powerful signal is not only immune to jamming and spoofing but is also available even inside buildings.

NextNav relied on terrestrial network of long-range broadcast beacons, which transmit GPS-like signals in the sub-Hertz range to measure ranges. The advantage of this technology is that the required signal can be obtained using chipsHEAets already available on the market. Moreover, it can also be used for navigation indoors and in densely packed urban environments, and when used in a barometric data system, it will be possible to determine the vertical coordinate.

Finally, the results of the completed work were announced in early 2021 [43]. It turned out that none of the 11 candidate technologies could universally backup the positioning and navigation capabilities provided by GPS and its augmentations. All companies proposed some PNT performance of value, but only NextNav demonstrated the technology which was promising from the practical point of view. With a terrestrial network of transmitters deployed all over the country, TerraPoint's signal transmitted at a frequency of 900 MHz is more than 100 000 times stronger than that of GPS.

NextNav, which was founded in 2007 and had only 61 employees in 2021, continued its research after the tender and, in the summer 2023, tested its PNT TerraPoiNT system with LTE (providing data transmission at a speed of about 100 Mbit/s) and 5G signals, demonstrating that this solution is a viable alternative to GPS [57]. The test results came after the European Joint Research Centre (JRC) report released earlier that year highlighting NextNav's TerraPoiNT among the other technologies that met or exceeded relevant standards for existing GPS technologies. NextNav's solution offers both horizontal and vertical location services while remaining commercially available and cost-effective for end-users.

According to the press release, during the testing, TerraPoiNT demonstrated indoor positioning, timing and navigation, including vertical location accuracy within 2 m 90% of the time. In addition, timing stability was within 15 ns 90% of the time.

2. The US Air Force considered the possibility of using magnetic fields instead of GPS, and primarily over the water surface [44]. To this end, the Air Force Institute of Technology (AFIT) studied the magnetic anomaly navigation technique (MAGNAV).

Air Force Major Aaron J. Canciani, an Assistant Professor of Electrical Engineering at AFIT, has been at work designing algorithms for MAGNAV flight testing for several years. Canciani says there are four pillars to MAGNAV – magnetic maps, sensors, positioning algorithms and calibration of sensors. He can't stand the question of MAGNAV accuracy, realizing that everyone will be comparing it to GPS. "One of the worst things people do when they discuss alternative PNT is to pretend that everything needs GPS accuracy," he says.

In ideal conditions (high-quality map, low altitudes, and a fast-moving platform), MAGNAV could be accurate to 10 meters. However, in different conditions and with lower quality magnetic maps, this error increases to 1 km and it is no longer possible to talk of any GPS backup.

3. Since 2021, the European Union has been exploring alternative PNT through a prefeasibility study and technological demonstration of six different non-GNSS positioning, navigation, or timing solutions from six different companies, including Locata Corporation (Australia), Satelles Inc. (US), GMV Aerospace (Spain), OPNT BV (the Netherlands), Seven Solutions SL (Spain), and SPCTime (France). Each company was awarded an average of 70 000 euros [45].

Some of them studied the possibility of delivering positioning and/or timing information, independently from GNSS, while the others dealt with both problems. The results of the submitted research were analyzed by the EC JRC in Ispra (Italy), following which the final report on the project was published. Its results are supposed to be taken into consideration in the next version of the European Radio Navigation Plan.

In this case, too, as in the study conducted by the US Department of Transportation, only one participant was able to cope with the task. It was Locata [58] that uses technologies based on a family of radio beacons, each broadcasting time and positioning signals.

Locata demonstrated high positioning and timing performance across every test environment, delivering:

- cm-level positioning accuracy in all tests, indoor and outdoor, under static and kinematic conditions;
- picosecond-level time transfer using Locata's proprietary TimeLoc technology, over multiple media types including RF over distances of more than 105 kilometers and over fiberoptic and/or coaxial cables, without requiring satellites or atomic clocks.

4. The UK, which has fallen out of the European space development programs, is going its own way in search of original ways to take up the PNT challenges. Cutting-edge ways of navigating in the event of GPS disruption are being explored by innovative UK industry on behalf of Defence Equipment & Support (DE&S), which is part of the Ministry of Defence. The Alternative Navigation research has identified three possible routes to provide an alternate PNT solution and enhance the UK's resilience [46].

The new Space Delivery Team within DE&S, which is running the program, is focusing on resilient timing (improving timing accuracy), signal of opportunity (determining own position by using radio transmissions), and visual navigation (exploiting advances in imaging sensors to inform position).

The work, which is currently at the concept stage, will run until March 2024. The idea is then to narrow down the available options and demonstrate and assess prototypes to determine which ideas are worthy of implementation.

Seven contracts, at a total value of around £3.8-million, were placed with six companies based in the UK [July 2021]:

- Resilient Timing – Teledyne e2v, a Teledyne UK company UK;
- Signal of Opportunity – QinetiQ Ltd and Roke Manor Research Ltd;
- Visual Navigation – Forsberg Services Ltd; Horiba Mira Ltd; MBDA UK Ltd and Roke Manor Research.

The idea of creating a terrestrial navigation system to replace GNSS with similar characteristics, at least for the UK region and adjacent territories, is still on the agenda. Its discussion was spurred by a 1174-page publication of six British academic and analytic organizations recommending the integration of terrestrial and space systems to ensure that the UK's critical maritime commerce can function regardless of solar flares or jamming space signals [47].

5. The ever-increasing number of problems associated with GNSS signals caused by their jamming and spoofing forces not only military consumers, but also IMO to seek new approaches to the PNT solution in nonstandard ways. Recently, considerable attention has been paid to the R-Mode (or Ranging Mode), which uses existing maritime radio signals as ranging sources.

The idea of the method is to use these signals to measure the range to the transmitter with known coordinates. If there are several signals of this type, it is possible to calculate the position using the triangulation method. At the first stage, R-Mode research was carried out using medium-frequency signals transmitted by beacons of the GNSS differential correction system located on the sea coast, and high-frequency AIS signals [50]. Both kinds of signals are many times stronger than GNSS signals, which makes them less vulnerable to external influences.

It turned out that the structure of the AIS signal used to synchronize beacons meets the specified requirements (although these signals can be used at ranges not exceeding several tens of km), and the packet of the differential correction system should contain 2 signals with amplitude modulation, which ensures stable tracking of the signal in daytime conditions at ranges up to 550 km. At night, this range decreases. The error in range measurement using R-Mode is less than 10 m during the day and no more than 20 m at night.

Naturally, the positioning accuracy will significantly depend on the angle at which the position lines generated by the measurements intersect when the triangulation problem is being solved, i.e. HDOP value. The studies carried out in [51] show that in this region, beacons of the differential correction system installed on the shores of the North Sea provide HDOP = 2 and, accordingly, a maximum error (P = 0.997) in positioning in the R-Mode at a level 7 m during the daytime, while at night it reaches 20–30 m.

The R-Mode began to attract increasing attention due to the advent of VHF data exchange systems (VDES) that replaced AIS, with additional 100 kHz communication channels. While the AIS data rate is 9.6 kbit/s, for VDES, it reaches 307.2 kbit/s. And it is precisely these that the R-Mode developers are now focusing on.

5. SOME EXOTIC APPROACHES

All previously considered ways of addressing the PNT problems in general did not go beyond the scope of traditional radioelectronic technologies. Recently, researchers have set out in the directions never tried.

An original approach in this regard is demonstrated by the US Army Research Laboratory [48], whose specialists are trying to implement the ideas of quantum physics to attain the following objectives:

– provide improved PNT at GNSS-level accuracy over an interval of at least 7 days

without satellite technologies;

– improve precision timing in support of cyber operations and electronic warfare;

– GPS-independent PNT support for all branches of the armed forces with positioning error of no more than 10 m;

– creation of a GPS anti-jamming antenna.

The first idea is to use so-called entangled particles, which, even at a great distance from each other, behave as a single whole. When one of them is disturbed, the second reacts in an identical way. Einstein called the connection between entangled particles “spooky action at a distance.” They can be created by splitting any of them. Thus, two entangled photons can be produced from one by the laser impact on a certain type of crystal. The laboratory is trying to use such particles to solve synchronization problems and build ultra-wideband communication systems, which are also noise-free.

The second is to take advantage of the Rydberg technology, in which excited atoms emit a photon when their energy levels change. It was on this basis that the conception of an antenna capable of optically identifying and interpreting the flow of such photons generated by GPS satellite signals emerged. Obviously, such an antenna would be much more efficient than the existing ones in terms of tolerance to external effects.

2. The Office of Naval Research of the US Navy summed up the results of the competition to create an alternative GPS navigation system designed primarily for the Arctic to provide positioning error comparable to GNSS accuracy [49].

The winner was a team of researchers from Japan, UK, the USA and Finland, led by Dr. Chris Steer from the spinout company Geoptic. They are going to use a natural source of radiation called cosmic ray muons as an alternative to satellite signals. What makes this idea unique is that these subatomic particles pass through rock, buildings and the earth – areas where GPS communications cannot be received.

“The ability to navigate in Polar Regions will be of increasing importance in the coming decades as climate change is opening up Arctic waterways to commercial and military activities,” said Dr. Charles Eddy, the lead science director. “This project, which uses cosmic relativistic particles that continuously impinge on the Earth’s entire surface, offers an innovative approach to the challenge of navigation at high latitudes with little or no GPS service.”

According to the developers, each minute, about 10 000 cosmic ray muons reach one square meter of Earth; the researchers use them to depict the interior of the infrastructure under study. By placing cosmic ray detectors under an object, they can determine how much of them are absorbed as they pass through the region of interest. Muon technology has previously been used for imaging railway infrastructure (tunnels), construction site imaging, mining, oil and gas exploration, and nuclear waste testing.

“Like echolocation, the timing difference between ‘pings’ – the signals from a crossing muon in our detectors – can allow the user to measure the distance from one detector to another with multiple detectors allowing location by triangulation”, says Dr Steer. “The technique has already been tested in the laboratory before, where the process of converting particles’ crossing times to infer the position of a detector was successfully demonstrated.”

After initial testing of the system in a large water-immersion tank in the UK, the project will move to Finland to deploy into an Arctic lake that is covered by one meter of ice. At high latitudes, conventional GPS measurements are problematic due their orbital constraints.

A significant challenge for this project is to deploy a number of sensors, such as a highly synchronized set of distributed clocks (to better than 10 billionths of a second) in order to minimize the expected position uncertainty, as well as integrate them with muon detectors.

“We also need to deploy our system in Arctic weather conditions (typically – 20 degrees Celsius), in an isolated environment and partially underwater,” Steer added. “The cold environment has implications across many aspects of the project from personnel to ensuring the electronics are cold-resistant. The sea is broadly transparent to cosmic ray muons, so we expect there to be a number of scientific subsea navigation opportunities,” Steer continued.

Readers interested in the problems of muon navigation will find it useful to read the article [61].

3. The ASPN (All Source Positioning and Navigation) project, which involves the use of so-called signals of opportunity, which were previously not widely used for navigation problem solution, also served the purpose of GPS backup. It is believed that such signals are much more numerous than those supplied by GPS and, most importantly, much stronger than the latter, which makes it possible to have the PNT solution for an object in conditions of GPS signal outages.

It is noteworthy that signals of opportunity also include lightning flashes, accompanied by millisecond pulses at a frequency of 3–30 kHz, propagating over distances of thousands of kilometers and can be processed by geolocation methods using a network of special receivers. There are several global receiver networks, such as the 800-sensor Earth Networks Total Lightning Network (ENTLN). Also used are less exotic signals, primarily those from TV and radio stations.

The philosophy of this program was formulated by Lin Haas [52], a program manager in DARPA’s strategic technology office: “Can we develop a navigation system that can extract spatial and temporal information from any sensor, such as communication and imaging systems?” says Haas. “The answer is yes, of course you can.” Obviously, in this case, sensor is taken to mean sources of navigation information, including emitters of signals of opportunity.

However, DARPA's requirements go much beyond that: it is expected that the development will allow the system to be rapidly reconfigured, as the object moves and the composition of the sensors changes, without a lengthy retuning of the navigation filter. Provision should be taken to block data from sensors that the system had never seen before.

The work on the ASPN project was carried out quite extensively [53]. At the first stage, DARPA engaged the Charles Stark Draper Laboratory ($600 000) and Argon ST Inc., which is a multidisciplinary department of Boeing. They focused on developing the system architecture and navigation filtering algorithms, ensuring the integration of navigation sensors and rapid reconfiguration of the system. In doing so, they were able to show that adapting the system to different sensors and making it plug-and-play was feasible.

At the second stage, other US research firms joined the ASPN project: SAIC Inc. ($2.9 million), Vesperix Corp. ($100 000), SRI International ($1.3 million) and Systems & Technology Research ($314 000). They were supposed not only to complete the work begun, but also create a system prototype and real-time algorithms in order to confirm the ability to process an arbitrary set of input signals regardless of the conventional application of the sensors used. Clearly, as in all other DARPA-funded projects, the relevant stringent requirements for SWaP+C (size, weight, power consumption and cost) were also to be confirmed.

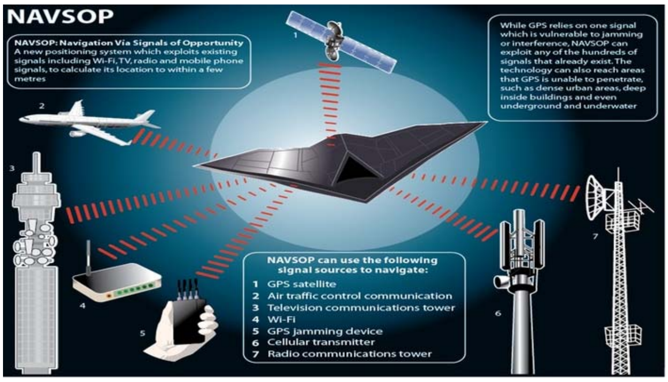
ASPN research was further developed by the Spatial, Temporal and Orientation Information in Contested Environments (STOIC) project, funded by DARPA through the U.S. Air Force Research Laboratory since 2015. The work was carried out by Rockwell Collins ($5.4 million), Raytheon BBN Technologies ($1.7 million), and Expedition Technology ($524 000 thousand) [54].

The STOIC program will seek to develop PNT systems that provide GPS-independent PNT with GPS-level timing and positioning performance. To do this, experts must combine long-range reference signals, ultra-stable tactical clocks, and multifunctional systems that share PNT information among users.

The goal of the STOIC program is to develop a PNT system that does not use GPS signals to provide PNT with GPS-level timing and positioning performance. It is based on long-range signals, ultra-stable time sources and multifunctional systems that share PNT information among users. The latter, by the way, is based on the ideas developed by Dorota Grejner-Brzezinska in the implementation of so-called group navigation (see, for example, [55]) in conditions of GPS outages in urban environments.

John Borghese, Vice President at Rockwell Collins stated the following: “The technologies we are developing to transmit time and navigation data are aimed at providing the ability to solve the problem of relative positioning of a distributed group of platforms in the absence of GPS signals”.

4. BAE Systems (UK) also conducted research on navigation via signals of opportunity, known as NAVSOP [56]. In an attempt to determine the user’s position with an error not exceeding a few meters, the scientists took advantage of existing transmissions such as Wi-Fi, TV and radio, mobile phone signals, along with GPS signals, and, most surprisingly, even GPS “jammers” (see Fig. 3). This technology turns out to be extremely effective, for example, in dense urban areas in places where GPS signals are unavailable for different reasons.



NAVSOP: Navigation Via Signals of Opportunity
A new positioning system which exploits existing signals including Wi-Fi, TV, radio and mobile phone signals, to calculate its location to within a few metres

While GPS relies on one signal which is vulnerable to jamming or interference, NAVSOP can exploit any of the hundreds of signals that already exist. The technology can also reach areas that GPS is unable to penetrate, such as dense urban areas, deep inside buildings and even underground and underwater

NAVSOP can use the following signal sources to navigate:
1 GPS satellite
2 Air traffic control communication
3 Television communications tower
4 Wi-Fi
5 GPS jamming device
6 Cellular transmitter
7 Radio communications tower

Fig. 3. NAVSOP structure.

The advantage of such a system is that all the infrastructure required to make it work already exists; you just need to learn how to use it effectively. Considering that NAVSOP uses radio wave signals of various ranges, the system can operate not only in forests or inside buildings, where GPS signals are blocked, but also in the most remote parts of the planet, including the Arctic and Antarctic, receiving signals from various satellites that are not intended for navigation.

6. CONCLUSIONS

Summarizing the above, we can state the following.

1. In the case of GPS, which has low transmitted signal power, not only spoofing but also jamming entail serious problems in practice, which the developers have to counteract primarily by creating special types of receiving antennas and using new types of signals. In integrated systems, precision inertial technologies help to solve these problems.

2. If we are talking about the accuracy of positioning equivalent to GPS accuracy, only the proposals of NextNav (USA) and Locata Corporation (Australia) deserve attention. However, taking into account the need to cover the positioning area with a field of radio beacons, it becomes obvious that in this case we can only talk about the local case of PNT.

3. If you increase the positioning error to an order of 10–20 m and forget about the needs of unmanned mobile platforms, which will serve the solution of positioning tasks in more than 80–90% of cases, you can use

- the modernized version of systems such as Starlink and One Web when fully deployed – at the global level;
- the differential version of the eLoran system – at the regional level.

4. As for the methods discussed in the section SOME EXOTIC APPROACHES, they are clearly search methods that can only provide a solution to the PNT problem at the local level, and today are not capable of guaranteeing accuracies in any way comparable to those of GPS. The latter also applies to methods of navigation by geophysical fields, be it magnetic, gravimetric or depth fields.

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

REFERENCES

1. Knight, R., Stanford PNT Symposium Marks 50 Years of GPS, Covers Various Emerging Topics, Inside GNSS, November 20, 2023. https://insidegnss.com/stanford-pnt-symposium-marks-50-years-of-gps-covers-various-emerging-topics/
2. Last, D., The Navigation of Navigation, IAIN World Congress, Proc. Non-IEEE Full Papers, 2015, pp. 8–13.
3. At ENC 2014: A GNSS Wake Up Call for Europe, Inside GNSS, 2014, April 16. https://insidegnss.com/at-enc-2014-a-gnss-wake-up-call-for-europe/.
4. New GPS ‘circle spoofing’ moves ship locations thousands of miles, GPS World, 2020, May 26. https://rntfnd.org/2020/05/26/new-gps-circle-spoofing-moves-ship-locations-thousands-of-miles-gps-world/.
5. Harris, M., Ghost ships, crop circles, and soft gold: A GPS mystery in Shanghai, MIT Technology Review, 2019, November 15.
6. Beyond GPS: 5 Next-Generation Technologies for Positioning, Navigation & Timing (PNT), DARPA, 7/24/2014. www.darpa.mil/news-events/2014-07-24.
7. Ward, N. and Bransby, M., Requirements for Resilient PNT, Proc. 2015 International Technical Meeting of The Institute of Navigation, Dana Point, California, pp. 234–238. https://www.ion.org/publications/abstract.cfm?articleID=12621.
8. Orolia fortifies resilient PNT with Satelles satellite time and location signal, GPS World, December 15, 2016. http://gpsworld.com/orolia-fortifies-resilient-pnt-with-satelles-satellite-time-and-location-signal
9. Mann, A., Scientists create their own GPS by spying on internet satellites, Science, Sep 27, 2021. DOI: 10.1126/science.acx9205
10. Soualle, F., Perspectives of PNT Services Supported by Mega Constellations, International Technical Symposium on Navigation and Timing (ITSNT), Toulouse, 14th November, 2018, ENAC.
11. Foust, J., ESA seeks funding for navigation technology programs at ministerial, SpaceNews, November 12, 2022.
12. Cozzens, T., ESA plans for low-orbiting navigation satellites, GPS world, October 31, 2022.
13. https://vpk.name/news/412705_ft_velikobritaniya_mozhet_sozdat_sistemu_sputnikovoi_navigacii_na_platforme_oneweb.html
14. https://news.rambler.ru/tech/46352531-telegraph-velikobritaniya-mozhet-sozdat-sistemu-sputnikovoy-navigatsii-s-pomoschyu-oneweb/
15. Meng, Y. et al., A Global Navigation Augmentation System Based on LEO Communication Constellation, 2018 European Navigation Conference (ENC), Gothenburg, Sweden, 2018, pp. 65–71, DOI: 10.1109/EURONAV.2018.8433242.
16. https://www.orolia.com/ws-dev/wp-content/uploads/2021/07/STL-infographic_0-1.pdf
17. https://openpnt.org/about-the-alliance/
18. https://insidegnss.com/darpa-plans-to-put-pnt-in-leo/
19. Lye, H., Project Blackjack: DARPA’s LEO satellites take off, Defense Technology, Space, July 2020, Is.113 https://defence.nridigital.com/global_defence_technology_jul20/blackjack-darpa-satellites
20. https://breakingdefense.com/2019/08/army-seeks-small-satellites-to-support-ground-troops/
21. GPS-Navigation Central to Space Development Agency’s New LEO Constellation, ION Newsletter, vol. 32, no.1, Winter 2022, pp. 1.

https://www.ion.org/newsletter/upload/ION-Winter22.pdf

22. Rainbow, J., Xona Space Systems fully funds GPS-alternative demo mission, Spacenews, September 22, 2021. https://spacenews.com/xona-space-systems-fully-funds-gps-alternative-demo-mission/
23. Knight, R., NovAtel receivers to support new Xona commercial LEO constellation. Inside GNSS, May 31, 2022. https://insidegnss.com/novatel-receivers-to-support-new-xona-commercial-leo-constellation/
24. Harris, M., Starlink signals can be reverse-engineered to work like GPS – whether SpaceX likes it or not, MIT Technology Review, Space, October 21, 2022.
25. Divis, D.N., Space development agency plans to create an alternative GPS constellation, Inside GNSS, June 24, 2019. https://insidegnss.com/space-development-agency-plans-to-create-an-alternative-gps-constellation/
26. Rivkin, B.S., European Navigation Conference ENC-GNSS 2014, Giroskopiya i navigatsiya, 2014, no. 2, pp. 151–160.
27. eLoran Time - Results fm 2016 Tests & Demos, Resilient Navigation and Timing Foundation, Jan 25, 2017. http://rntfnd.org/2017/01/25/eloran-time-results-fm-2016-tests-demos.
28. Congressmen Oppose NDGPS Plan Pending "Resilient PNT Architecture", Resilient Navigation and Timing Foundation, Mar 30, 2016. http://rntfnd.org/2016/03/30/congressmen-oppose-ndgps-plan-pending-resilient-pnt-architecture.
29. House Passes Bill Requiring eLoran to Safeguard GPS, Resilient Navigation and Timing Foundation, Jul. 24, 2017. https://rntfnd.org/2017/07/24/house-passes-bill-requiring-eloran-to-safeguard-gps/.
30. Saudi Arabia Upgrading to eLoran, Resilient Navigation and Timing Foundation, Jul. 09, 2023, https://rntfnd.org/2023/06/09/saudi-arabia-upgrading-to-eloran/
31. Lebekwe, C.K., Zungeru, A.M., and Astin, I., Meteorological Influence on eLoran Accuracy, IEEE Access, 2021, vol. 9, pp. 167162–167172. https://doi.org/10.1109/ACCESS.2021.3135707
32. Rivkin, B.S., Analiticheskii obzor sostoyanya issledovanii i razrabotok v oblasti navigatsii za rubezhom (Analytical Review of International Navigation Research), No. 1, St. Petersburg: Concern CSRI Elektropribor, JSC, 2017.
33. eDLoran: The Next-Gen Loran, GPS World, June 28, 2014. https://www.gpsworld.com/edloran-the-next-gen-loran/.
34. Seo, K. and Kim, M., eLoran in Korea – Current status and future plans, European Navigation Conference 2013. https://rntfnd.org/wp-content/uploads/2018/04/ENC 2013_JiwonSeo_revised.pdf
35. Son, P.-W., Rhee J.R., and Seo J., Novel multichain-based Loran positioning algorithm for resilient navigation, IEEE Transactions on Aerospace and Electronic Systems, 2007, vol. 43, no. 2, pp. 628–644.
36. Son, P.-W., Rhee, J.H., Han, Y., Seo, K., and Seo, J., Preliminary study of multichain-based Loran positioning accuracy for a dynamic user in South Korea, IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, USA, 2018, pp. 1034-1038. https://doi.org/10.1109/PLANS.2018.8373482
37. Goward, D., South Korea partners with broadcaster on eLoran and 10-cm GPS, GPS World, November 23, 2020. https://www.gpsworld.com/south-korea-partners-with-broadcaster-on-eloran-and-10-cm-gps/.
38. Goward, D., China expanding Loran as GNSS backup, GPS World, October 12, 2020, https://www.gpsworld.com/china-expanding-loran-as-gnss-backup/.
39. Goward, D., $15M for GPS backup demo part of Congress' march to terrestrial PNT, GPS World, January 16, 2019. https://www.gpsworld.com/15m-for-gps-backup-demo-part-0f-congress-march-to-terrestrial-pnt/
40. Goward, D., GPS to get terrestrial backup system, GPS World, December 5, 2018. https://www.gpsworld.com/gps-to-get-terrestrial-backup-system/
41. Divis, D.A., 11 Firms Chosen to Demonstrate GPS Backup Technologies, Inside GNSS, Resilient Navigation and Timing Foundation, November 8, 2019. https://rntfnd.org/2019/11/09/11-firms-chosen-to-demonstrate-gps-backup-technologies-inside-gnss
42. Goward, D., GPS backup demonstration projects explained, GPS World, January 9, 2020. https://www.gpsworld.com/gps-backup-demonstration-projects-explained/
43. DOT Report on Backup PNT Technologies Finds NextNav Performs Best, Calls for Synthesis and Synergy, Inside GNSS, January 22, 2021. https://insidegnss.com/dot-report-on-backup-pnt-technologies-finds-nextnav-performs-best-calls—for-synthesis-and-synergy/
44. Eric Tegler, Air force is looking at using magnetic fields to navigate instead of GPS and flight testing it on F-16s, Forbes, June 12, 2020. https://www.forbes.com/sites/erictegler/2020/06/12/air-force-gps-magnetic-fields-navigation-f-16/
45. Six Companies to Demonstrate Alternative PNT to European Union, Inside GNSS, October 19, 2021. https://insidegnss.com/six-companies-to-demonstrate-alternative-pnt-to-european-union/
46. DE&S commissions UK industry to explore Alternative Navigation Technologies, September 21, 2021 https://des.mod.uk/des-alternative-navigation-technologies-gps/
47. https://rntfnd.org/2020/06/22/us-to-uk-dont-build-another-gps-go-leo/
48. https://www.army-technology.com/features/quantum-sensing-atoms-military/?cf-view
49. How science is finding ways to navigate in GPS-denied environments, Office of Naval Research News Release 24-Nov-2021 https://www.eurekalert.org/news-releases/935931
50. Grundhöfer L, Rizzi F.G., Gewies. S., et al. Positioning with medium frequency R-Mode. Navigation, 2021, vol. 6, no. 4, pp. 829–841. https://doi.org/10.1002/navi.450
51. Rizzi, F.G., Phase Locked Loop for R-Mode navigation system, Master Degree Thesis, 2020. https://webthesis.biblio.polito.it/14408/1/tesi.pdf.

52. Kramer, D., DARPA looks beyond GPS for positioning, navigating, and timing, Physics Today, 2014, vol. 67, no. 10, pp. 23–26 https://doi.org/10.1063/PT.3.2543
53. Keller, J., Three join DARPA ASPN navigation sensor-fusion program to reduce U.S. need for GPS. Military&Aerospace Electronics, February 2013. http://www.militaryaerospace.com/articles/2013/02/Three-join-ASPN.html
54. Keller, J., Three companies set sights on precision navigation that works independently of GPS, Military+Aerospace Electronics, Sept. 25, 2015 www.militaryaerospace.com/articles/2015/09/navigation-without-gps.html.
55. Lee, J.K., Grejner-Brzezinska, D.A., and Toth, Ch., Network-based collaborative navigation in GPS-denied environment, Journal of Navigation, 2012, vol. 65, no. 3, pp. 445–457. DOI: 10.1017/S0373463312000069
56. Navigation via Signals of Opportunity (NAVSOP) www.baesystems.com/en/product/navigation-via-signals-of-opportunity-navsop.
57. NextNav Tests Alternative PNT Solution, Achieves Accurate 3D Position with LTE and 5G Signals, Inside GNSS, July 25, 2023. https://insidegnss.com/nextnav-tests-alternative-pnt-solution-achieves-accurate-3d-position-with-lte-and-5g-signals/
58. Luccio, M., Centimeters and picoseconds without satellites or atomic clocks, April 4, 2023. https://www.gpsworld.com/centimeters-and-picoseconds-without-satellites-or-atomic-clocks/
59. Peshekhonov, V.G., High-precision navigation independently of Global Navigation Satellite Systems data, Gyroscopy and Navigation, 2022, vol. 13, no. 1, pp. 1–6. https://doi.org/10.1134/S2075108722010059
60. Schmidt, G.T., GPS based navigation systems in difficult environments, Gyroscopy and Navigation, 2019, vol. 10, no. 2, pp. 41–53. https://doi.org/10.1134/S207510871902007X
61. Stepanov, A.P., Achievements of nuclear physics in the light of solving the problem of locating a moving object by means of relativistic particles, Navigatsiya i gidrografiya, no. 72, pp. 24–57.
62. Seo, K., Park, S.H, Fang, T.H., and Lee, S.H., Analysis of Positioning Performance to Meet HEA Requirement in eLoran Testbed, International Association of Institute of Navigation (IAIN), 2018.