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High-Precision Navigation Independently of Global Navigation Satellite Systems Data

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Abstract—In recent years, it has become clear that global navigation satellite systems (GNSS) have insufficient immunity to noises. In this regard, the paper discusses possible methods and tools ensuring high-precision navigation measurements without using GNSS, and their current development status.

Keywords: GNSS interference, integrated INS/GNSS systems, autonomous navigation tools, radio navigation

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INTRODUCTION

GNSS have made a revolution in the field of navigation thanks to the unique combination of their performance features: the accuracy of location coordinates up to several meters (and later up to several decimeters), global availability of information at any point on the Earth's surface, at any time and under any weather conditions; and small size and low cost of receiving equipment.

To date, four GNSS with a total of 130 satellites have been deployed: GLONASS (Russia), GPS (USA), BeiDou (China), and Galileo (European Union). Up to 30 of these satellites can be observed simultaneously; but even four of them are enough to determine the coordinates and time. The number of local navigation satellite systems is increasing; the largest of them are QZSS, MSAS (Japan), GAGAN and NAVIC (India), EGNOS (EU), WAAS (USA), and BDSBAS (China).

Modern vehicles and traffic management systems are inconceivable without GNSS. Most people of the Earth use GNSS in their everyday life. In the armed forces, the combat platforms (aircraft, ships, tanks, etc.), high-precision weapons and even individual servicemen receive the positioning and timing information from GNSS. The dependence on the satellite navigation has become universal.

Nevertheless, the problem still exists. It is important for the users to receive the positioning and timing data continuously and without any distortions; however, GNSS is not always able to meet this requirement.

Firstly, the GNSS signal is emitted in the UHF band; it does not penetrate the sea water, under the ground, through the walls of structures; it is shaded by high buildings and the walls of narrow canyons, and weakened by thick crowns of trees.

Secondly, since the satellites have a limited power resource, the signal power near the Earth surface is only 10^{-16} W, and it is easy to create interference with such a weak signal. There are a lot of examples proving this fact.

Thirdly, it is easy to apply spoofing, i.e. to introduce some changes in the signal (to be more precise, in the pseudorange) received from GNSS. As a result, the distorted coordinates can have any values.

The problem of insufficient noise immunity of GNSS seems to have been stated for the first time at the governmental level in the US by the committee headed by D. Rumsfeld (2001) who studied the development of satellite navigation in terms of national security.

The developers of GPS increased the noise immunity of the system by means of signal coding. The civil code C/A provides stable reception of signals with the noise-to-signal ratio up to 250. When using the code P(Y), consistent reception of information is provided at the noise-to-signal ratio equal to 2500. However, if the noise power near the receiver exceeds 2×10^{-12} W, there is a risk of signal loss [1].

For this reason, the methods for complementing or substituting the GNSS with noise-immune navigation tools are searched for. In 2018, in the US a law was passed, which obligated the US Department of Transportation to create a GPS redundancy system which would be terrestrial, wireless, non-destructive, and the signal of which would be available under the ground and inside buildings. The Department selected 11 organizations who proposed various solutions to the problem. In the report presented in early 2021 [2], it is proposed to use a number of technologies: satellite broadcasting in L-band, terrestrial navigation systems working in LF and UHF bands, fiber-optic lines for transmitting the precise time and for clocking the transmitters. No universal noise-immune tool to fully replace the GNSS was proposed.

The US Department of Defense (DoD) did not show any activity is this search, probably focusing on the potential use of high-fidelity M-code and narrow-beam antennas increasing the signal level by two orders of magnitude. Moreover, the US DoD DARPA is a sponsor of Northrop Grumman's Blackjack Program [3] which is aimed at the development of low-orbit satellites constellation for high-speed communication and navigation.

Nevertheless, the US Senate Armed Forces Committee, referring to the requirement of combatant commanders, included the order for the DoD to mature, test and acquire for prioritized missions the equipment to generate resilient alternative positioning, navigation and timing (PNT) signals [4].

The Gyroscopy and Navigation journal has already addressed the problem of GNSS noise immunity improvement [1]. This paper gives an assessment of possible methods for GNSS replacement. In this case, it is not necessary for the replacing system to ensure the accuracy up to several meters. For many missions, the error larger by an order of magnitude will be satisfactory.

We will consider three groups of tools that can replace GNSS: short-time, global, and local.

GNSS SHORT-TERM REPLACEMENT

Historically, the first method that provided continuous acquisition of navigation information during short outages of GNSS signals, e.g., while driving in the streets with tall buildings, consisted in the INS/GNSS integration. The combination of GNSS properties (high accuracy of positioning without accumulating errors over time, but lack of spatial memory) with those of an inertial navigation system (spatial memory, but error accumulation over time) was used for constructing an integrated system which ensured continuous reception of information.

However, there is another condition which is fully met by GNSS receiving equipment and can hardly be met by an inertial system. It is a requirement for extremely small size, power consumption and cost. The only type of gyroscopic elements which is comparable to GNSS receiving equipment by these parameters is micromechanical gyroscopes (MMG) and accelerometers (MMA). They are used in an inertial measurement unit (IMU) consisting of a triad of MMG and a triad of MMA. The MMG have a large drift, so the IMU can only be used for short-term replacement of GNSS.

An integrated system functions as follows. As long as the GNSS signal is available, it is transmitted to the system output and at the same time is used for MMG calibration. When the GNSS signal disappears, the system switches over automatically in the mode of IMU data output.

The first integrated systems were based on miniature rotor vibratory gyroscopes (RVG). The tests carried out in mid-1990s on a car moving in the city streets [5] with an IMU based on an RVG and an accelerometer of accuracy grade 10 deg/h and 10^{-3} m/s^2, respectively, showed that the error of the integrated system did not exceed 50 m over the period of GNSS outage lasting for 100 s, and in 95% of samples this error was not more than 20 m.

At present, there are MMG with the zero drift of about 1–10 deg/h, and multi-mass MMG have been created, with a drift lower by an order of magnitude [6, 7] and with a respectively increased time of GNSS replacement.

Another resource for increasing the GNSS replacement time consists in the use of ground speed measurements in addition to the inertial data. The resulting error will grow much slower than the inertial system error. The SINS is corrected using the methods of zero velocity potential update (ZUPT correction) and by the SINS integration with an odometer [8].

Charles Draper Laboratory (USA) proposed a new deeply-coupled integrated scheme to improve noise immunity [1]. Its architecture includes a nonlinear Kalman filter with coefficients continuously adjusting to the changes in the signal-to-noise ratio (Fig. 1). The improvement of noise immunity by 10–15 dB was verified by experiments.

Integrated INS/GNSS systems are used, in particular, for ensuring the noise immunity of tactical weapons. This is the principle that the navigation support of Excalibur artillery shell is based on [9]; the US army applied this shell in Iraq and Afghanistan wars. However, its use was limited due to high cost.

POSSIBILITY OF GNSS GLOBAL REPLACEMENT

Global replacement of GNSS with a noise-immune navigation tool without any limitations on coordinates and time is possible either by creating a satellite system with a stronger (by several orders of magnitude) signal, or by using autonomous navigation tools.

In the first case, an obvious way to increase the signal strength is to lower the spacecraft orbits. With the same antenna orientation, the signal changes inversely as the square of the spacecraft orbit altitude; therefore, if the standard GNSS orbit altitude of 20000 km is reduced to 600 km, the signal will become stronger by

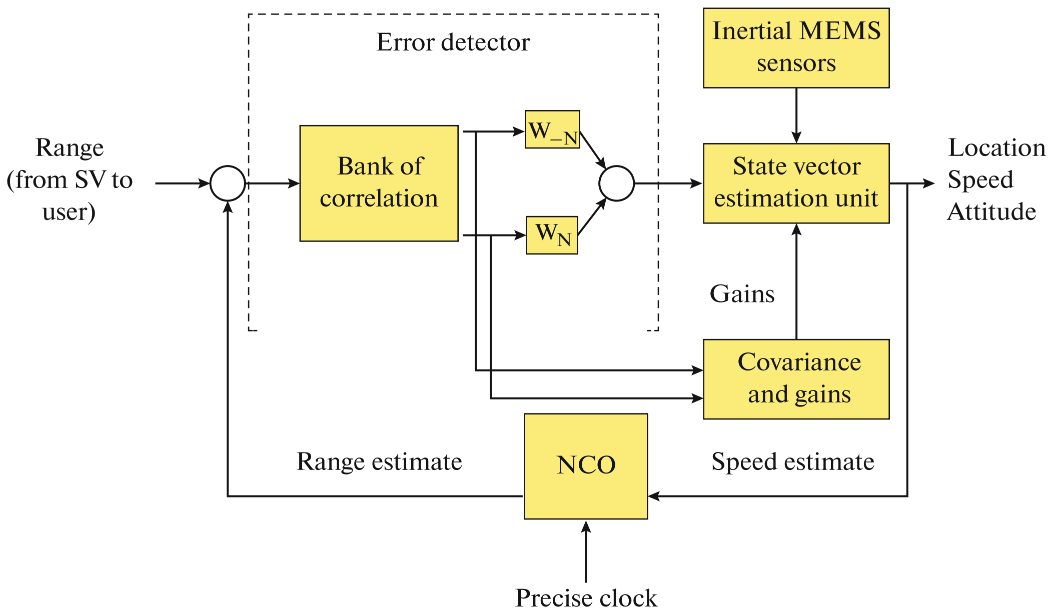


Fig. 1. Deeply-integrated system [1].

three orders of magnitude, and it will be much more difficult to create interference with such a signal (especially when it is encoded).

However, lowering the orbit altitude will reduce the area on the Earth surface, where the signal arrives, so it will be necessary to increase the number of satellites to ensure continuous coverage of the entire globe surface. The problem will be solved if we use a constellation of low-orbit spacecraft ensuring, for example, broadband communication. Currently, groups of hundreds low-orbit satellites are being formed, and such a solution for noise immunity of satellite navigation appears to be quite realistic.

An inertial navigation system (INS) is an autonomous navigation tool that has no limitations on positioning data generation. The initial information for the INS are the Earth angular rate and the acceleration of the platform whose motion parameters are determined by the INS. It is impossible to create any interference with such a system.

In recent decades, strapdown INS (SINS) on wave optical gyroscopes, laser gyroscopes (LG) and fiber-optic gyroscopes (FOG) with a zero drift at the level of 10^{-2}–10^{-3} deg/h have been used. They can replace GNSS for about 10 min. At the same time, the FOG drift is expected to decrease by an order of magnitude [10] and, accordingly, the time of GNSS replacement will increase up to one hour. However, the size, energy consumption and cost of SINS exceed those of GNSS receivers by two orders of magnitude. The accuracy of INS on precision electrostatic gyroscopes (INS EG) is higher than that of FOG-based SINS, but its dimensions, energy consumption and cost are even higher than those of the latter. Therefore, the INS EG is only used where GNSS signals do not penetrate, i.e. on submarines.

The expected reduction in the SINS size and energy consumption is associated with the use of new types of gyroscopes (Fig. 2). A wave solid-state gyroscope (WSG) will reduce the SINS volume by about half compared to LG- and FOG-based SINS with currently comparable accuracy [10, 11]. The prototype of a gyroscope based on the effect of nuclear magnetic resonance (NMG) is close to MMG in terms of size and has a zero drift by at least an order of magnitude lower than the latter [12]. At the same time, it should be borne in mind that the cost of NMG will certainly be higher than that of MMG.

It will be possible to radically approach GNSS if a gyroscope based on matter waves (de Broglie waves) is created [13]. However, today there are only laboratory installations, and many issues of principle for this gyroscope implementation have not been resolved yet.

Another method of GNSS substitution is based on the principles of celestial navigation. This method has long been used in the navy and, in some cases, in rocket and space technology. However, until recently, its accuracy did not match the accuracy of GNSS. The situation changed with the invention of a recording device—an astrotelescope based on a CMOS matrix, and a correlation-extreme method for determining the position of star images on it with an error of tenths of an arc second with an observation time of up to one hour [14]. In addition to quite a long session of stars observation, a serious limitation of the celestial navigation method is the need for optical visibility of stars.

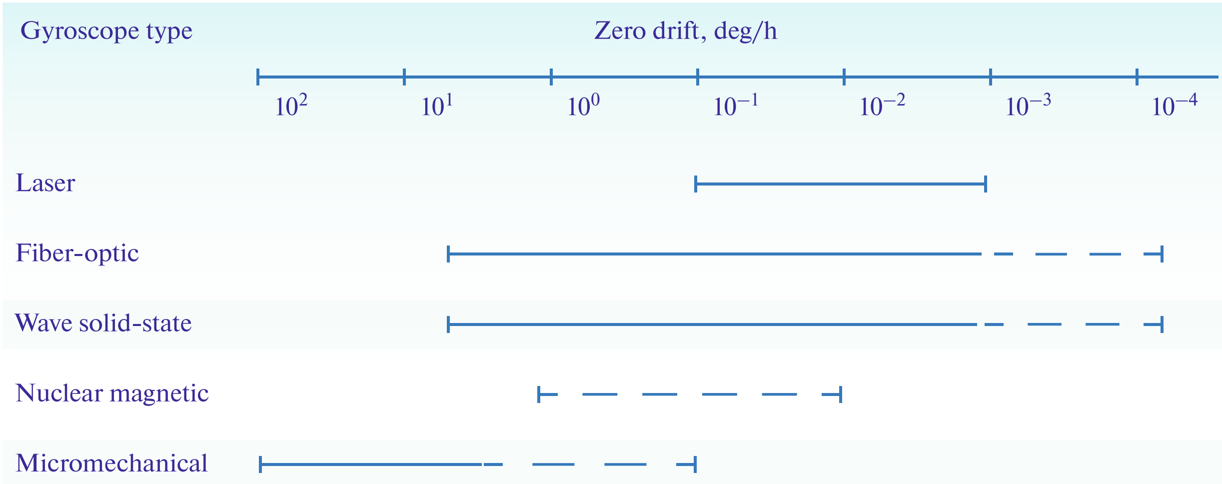
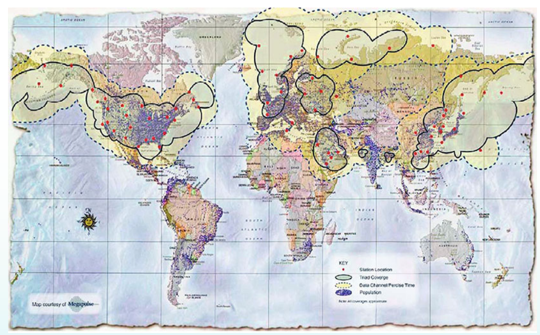


Fig. 2. Accuracy characteristics of modern gyroscopes (solid line); expected increase in accuracy characteristics (dash line).

RMS error of positioning	
Chaika	Loran-C
100–700 m	≤230 m
Differential method—error 50 m within a radius of 150–200 km	
Operation coverage area	
20 mln sq. km	95 mln sq. km



Map of regions covered by Loran-C and Chaika systems

Fig. 3. Performance of Loran-C and Chaika radio navigation systems.

GNSS REPLACEMENT IN LOCAL AREAS

Before GNSS appeared, Loran-C radio navigation system (the Russian equivalent Chaika) was actively developing, and its chains covered a significant part of the Earth surface (Fig. 3). However, the Loran-C system lost the competition with GNSS which provided two orders of magnitude higher accuracy and was globally available. As a result, Loran-C systems were decommissioned everywhere, some stations were conserved, and some were liquidated.

When the discussion of GNSS complement/replacement problem began, it was proposed to develop an advanced e-Loran system [15]. High noise immunity of e-Loran system is to be ensured by the power of oscillators (about 1 MW versus 50 W for GNSS). Low frequency of the signal (100 kHz) will make it possible to take navigation measurements in buildings, in the forest, or under the ground surface.

The e-Loran system should ensure the positioning accuracy of 8–20 m and the timing accuracy of 50 ns [15]. The estimated cost of the e-Loran system deployment in the US is $400 million, but there is no information yet on the allocation of appropriate funds.

Already in 2014, the UK launched e-Loran stations to support navigation at the eastern coast and the port calls on this coast. In South Korea, in addition to the coast, e-Loran chains are involved in some part of the country's territory due to the unfavorable interference situation when using GNSS.

As for other electronic facilities, Wi-Fi access points and radio beacons can be undoubtedly used for navigation measurements within buildings and structures. Acoustic beacons are used under water. The error in determining the coordinates is 5 m at a distance of 100 m to the beacon, and hundreds of meters at a distance of 10 km. It should be noted, however, that radio navigation aids are non-autonomous, and can easily be detected and disabled.

A mobile ground-based pseudo-satellite system consisting of three pseudo-satellite beacons is also proposed [16], which provides a coverage area with a diameter of 20 to 40 km depending on the antenna height.

In recent decades, correlation-extreme methods of navigation, or map-aided navigation based on the Earth geophysical fields have been developing; surface fields are the terrain and the bottom of the seas and oceans, and potential fields are gravitational and magnetic ones.

The accuracy of navigation measurements using the correlation-extreme method depends on the error of the Earth's geophysical field map plotting, the magnitude of the field gradient and the error of navigation measuring instruments. In turn, the error of the map plotting depends on the errors of the measuring device and survey coordination.

Analysis of marine gravimetric maps has shown that in most of the World Ocean waters, the gradient of the gravitational field is insufficient for high-precision positioning, but there are some limited areas where the gradient is 3 mGal/km or more. With the error of modern marine relative gravimeters being about 0.1 mGal, the location coordinates can be determined in these areas with an error of less than 100 m [14]. It should be noted that it is not the instrumental error of the gravimeter sensitive element that is given, but the full value of the error, taking into account the corrections for Eotvos, Harrison and cross-coupling effects.

Modern absolute gravimeters have one or two orders of magnitude lower instrumental error than relative ones, but there is no experience of their operation on mobile platforms, so it is difficult to estimate the total error in these conditions.

Bathymetric fields (bottom relief) are correlated with the gravitational field and provide the accuracy of navigation measurements close to gravimetric fields.

As for the Earth's magnetic field (EMF), the situation is as follows. Modern tools for measuring its parameters ensure the sensitivity at the level of 1 nT. This could actually provide the positioning error less than 100 m. Unfortunately, due to the presence of time variations and the need to separate the EMF and the magnetic field of the carrier, it is quite difficult to implement this method in practice. It should be noted that it might be possible to use EMG gradient sensors in the nearest future; however, extra studies are required to assess their potential application for the navigation purposes [17, 18].

CONCLUSIONS

Modern GNSS have limited noise immunity, and noise-proof navigation aids that complement or replace GNSS are essential for critical applications.

Currently, such aids are as follows:

• encoded signals in protected GNSS channels;

• integrated INS/GNSS systems (global short-term replacement of GNSS);

• high-precision strapdown inertial navigation systems (global replacement of GNSS lasting up to an hour);

• equipment for map-aided navigation based on the anomalies of geophysical fields—surface and potential (local navigation);

• systems of radio and acoustic beacons (local navigation, including indoors and under water).

Also, some new aids can be created:

• advanced e-Loran system (regional navigation);

• low-orbit satellite navigation system (global navigation).

Complete replacement of GNSS (globally and in terms of accuracy characteristics) is impossible yet, but the selection of aids is significant, and the aids sufficiently close to optimal can be chosen for specific application conditions.

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