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IMPROVING THE MEASUREMENT EFFICIENCY OF MARINE SHIP-BORNE RECEIVERS OF GLOBAL NAVIGATION SATELLITE SYSTEMS

Global navigation satellite systems (GNSS) play a decisive role in maritime navigation. The differential mode of operation of ship-based GNSS receivers using coordinate corrections allows to significantly increase the accuracy of positioning of a seagoing vessel compared to the autonomous mode. The object of the study was marine GNSS receivers capable of operating in differential mode.

This research examines the problems of reliably determining the actual operating mode of a shipboard GNSS receiver (autonomous or differential). It outlines the risks associated with the ambiguity and unreliability of standard differential mode indicators (flags posMode = D, Fix Quality = 2). This leads to misinterpretation of the accuracy status by related navigation systems, in particular, the Automatic Identification System (AIS), and poses a threat to maritime safety.

It has been experimentally proven that outdated receiver models can falsely indicate operation in differential mode, relying solely on user settings rather than the actual receipt and application of corrections. It has been established that modern receivers solve this problem but create a new level of complexity by separating the concepts of "accuracy" and "integrity" of the navigation solution. They can produce a highly accurate position while simultaneously flagging it as unreliable (NavStatus flag = V) if a faulty satellite is detected. A systemic conflict between the requirements of the International Telecommunication Union (ITU) and International Electrotechnical Commission (IEC) standards regarding high-accuracy criteria for AIS has been identified.

It has been established that inaccurate mode indications in outdated equipment are related to the particularities of its software logic, which links the mode flag to the setting rather than to the availability of data. The behavior of modern receivers is explained by the implementation of advanced integrity control algorithms (RAIM) and the logic of new standards (in particular, IEC 61108-7), which require reporting the loss of confidence in data.

The research results can be used by developers of marine equipment (AIS, ECDIS) to create comprehensive GNSS data analysis algorithms that take into account a set of indicators. International organizations (IMO, ITU) can use them to harmonize standards. Ship operators and technical specialists can use these results to form a correct understanding of the limitations of standard indicators and the need for a comprehensive assessment of the status of the GNSS receiver.

***Keywords**: navigation safety, AIS, positioning accuracy, differential mode, NMEA.*

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1. Introduction

A wide range of activities are carried out in coastal marine areas. These include transportation, dredging and hydraulic engineering works, fishing, and naval operations such as patrolling, mining, and rescue missions. All of these activities are critically dependent on accurate and reliable positioning.

Today, the main tool for accurate positioning is Global Navigation Satellite Systems (GNSS), which interact with the user's navigation equipment. For maritime navigation, the requirements for such equipment are regulated by the International Maritime Organization (IMO). Relevant resolutions, such as IMO MSC.112(73), IMO A.915(22) and IMO A.1046(27) [1–3], set out general requirements for these systems, including accuracy, which is about 10 meters for coastal waters. However, many specialized maritime operations (dredging, installation of underwater structures, hydrography) require sub-meter accuracy [4].

Improving the accuracy of vessel positioning using a differential correction mechanism is a pressing issue, the implementation of which is necessary for both operators of surface platforms and vessels performing work and operations, as well as external services to monitor their safety and efficiency.

Various aspects of improving the accuracy of vessel positioning using a differential correction mechanism are discussed in [5–7].

In [5], using Algeria as an example, it is demonstrated that the effectiveness of using EGNOS (European Geostationary Navigation Overlay Service) for positioning varies depending on the geographical location of the object relative to the signal integrity monitoring stations (RIMS).

Study [6] contains the results of an experimental assessment of positioning error deviation when using various methods of ionospheric delay compensation.

In [7], the positioning accuracy of DGPS and EGNOS receivers was evaluated using the example of a ship maneuvering in the Gulf of Gdańsk.

Reliable indication of the differential mode and the associated assessment of positioning accuracy is one of the key components of implementing this mechanism.

The starting point for the study was a critical error discovered during an experiment to test the possibility of improving positioning accuracy using publicly available differential services. When attempting to activate differential mode, it was found that the Samyung SPR-1400 GNSS receiver, widely used on ships, was transmitting unreliable information about its status. Thus, despite indicating differential mode, it actually continued to operate in autonomous mode (with low positioning accuracy), thereby misleading both the operator and related systems, in particular the ship's AIS transponder.

The discovery of this error prompted an investigation into whether this vulnerability was a special case associated with only one specific older model device or a systemic problem inherent in modern equipment.

This work is devoted to experimental research and determination of the mechanism leading to inaccurate indication of the differential mode. This is done by analyzing contradictions in NMEA messages from different generations of equipment.

The practical results of this study can be used as a basis for specific recommendations. This will allow:

- manufacturers of marine equipment – Automatic Identification System (AIS) and Electronic Chart Navigation and Information System (ECNIS) – to improve data processing algorithms;
- international organizations to initiate the harmonization of standards;
- navigators to correctly assess the reliability of the navigation information received.

All of this together will contribute to improving the safety of navigation.

2. Materials and Methods

2.1. Research object and hypothesis

Research object: marine GNSS receivers capable of operating in differential mode.

Subject of research: factors causing incorrect indication of GNSS receiver operating modes (e. g., posMode = D, Fix Quality = = 2 flags) and forming a false impression of navigation data accuracy.

Hypothesis: the problem of unreliable determination of the receiver's operating mode (differential or autonomous) is caused by the lack of a mechanism for deciding on the type of GNSS receiver operating mode based on a combination of NMEA message parameters.

2.2. Modern methods for improving the accuracy of marine GNSS equipment

2.2.1. Differential correction method

The task of improving positioning accuracy is solved by using GPS differential correction (DGPS) technologies. The essence of the method is to use a stationary base station with known coordinates, which calculates errors in satellite signals and transmits correction data to mobile users' navigation receivers. To transmit these corrections at sea, terrestrial and satellite communication channels are used:

- terrestrial radio beacons operating in the medium wave range (285–325 kHz) transmit corrections in RTCM SC-104 format [8];
- VHF and AIS channels: in some cases, VHF radio channels are used to transmit corrections, in particular messages in AIS format;
- Satellite-Based Augmentation Systems (SBAS), which are currently considered the primary means of distributing corrections.

2.2.2. Satellite-based augmentation systems (SBAS)

The SBAS architecture includes [9]:

1) a network of ground monitoring stations (RIMS) that track GNSS signals;

2) master control centers (MCC) that process data and calculate differential corrections (to orbits, satellite clocks, ionospheric delays) and integrity information;

3) uplink stations that send this information to geostationary satellites;

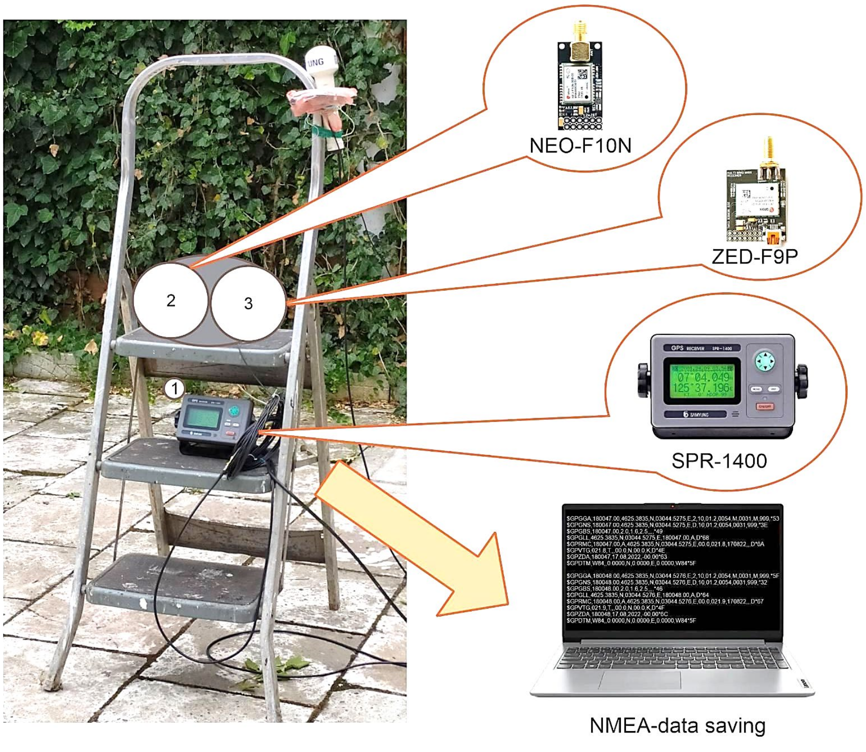
4) geostationary satellites (GEO), which broadcast corrections and integrity data to users over a large area.

For Europe, and in particular for the northwestern part of the Black Sea, this system is EGNOS. The presence of EGNOS coverage over this region provides all maritime users with the opportunity to receive free differential corrections that can significantly improve the accuracy of coordinate determination.

For example, for a point in the Odessa area (46°25.38′N, 30°44.52′E), which is located in the EGNOS coverage area, the expected gain in accuracy is quite significant. According to official reports on the system's performance, the positioning accuracy within the EGNOS Open Service is consistently less than 1–2 meters in the horizontal plane (95% of the time). Meanwhile, according to official US government data, the accuracy of standalone GPS is approximately 3–5 meters [10, 11]. Thus, the use of EGNOS allows for at least a 2–3-fold increase in positioning accuracy [12–14].

2.3. Experimental test bench for research

The following receivers were selected for experimental research: Samyung SPR-1400, u-blox NEO-F10N module, u-blox ZED-F9P module. The tests were conducted on an experimental test bench, the diagram of which is shown in Fig. 1.



```
$GPGGA,180047.00,4625.3835,N,03044.5275,E,2,10,01.2,0054,M,0031,M,999,*53
$GPGNS,180047.00,4625.3835,N,03044.5275,E,D,10,01.2,0054,0031,999,*3E
$GPGBS,180047.00,2.0,1.6,2.5,,,,*49
$GPGLL,4625.3835,N,03044.5275,E,180047.00,A,D*68
$GPRMC,180047.00,A,4625.3835,N,03044.5275,E,00.0,021.8,170822,,,D*6A
$GPVTG,021.8,T,,,00.0,N,00.0,K,D*4E
$GPZDA,180047,17,08,2022,-00,00*63
$GPDTM,W84,,0.0000,N,0.0000,E,0.0000,W84*5F

$GPGGA,180048.00,4625.3835,N,03044.5276,E,2,10,01.2,0054,M,0031,M,999,*5F
$GPGNS,180048.00,4625.3835,N,03044.5276,E,D,10,01.2,0054,0031,999,*32
$GPGBS,180048.00,2.0,1.6,2.5,,,,*46
$GPGLL,4625.3835,N,03044.5276,E,180048.00,A,D*64
$GPRMC,180048.00,A,4625.3835,N,03044.5276,E,00.0,021.9,170822,,,D*67
$GPVTG,021.9,T,,,00.0,N,00.0,K,D*4F
$GPZDA,180048,17,08,2022,-00,00*6C
$GPDTM,W84,,0.0000,N,0.0000,E,0.0000,W84*5F
```

Fig. 1. Test bench diagram

The GNSS antenna was installed at a height of 1.5 m above ground level and connected to the input of the corresponding receiver participating in the test. All received messages were transmitted from the receiver output via a digital data channel (using the NMEA 0183 protocol) to a personal computer, where they were stored for further analysis.

3. Results and Discussion

3.1. Study of the Samyung SPR-1400 standard marine GPS receiver

3.1.1. General information

Developed approximately in 2010, the Samyung SPR-1400 marine GPS receiver complies with the requirements of the current IEC 61108-1 standard [15] for marine GPS receivers and is currently widely used on ships. However, its architecture is based on a single-frequency L1 solution and does not support satellite augmentations, including SBAS/EGNOS. According to the technical documentation, in differential correction mode, the receiver is designed exclusively to receive corrections from an external ground-based DGPS beacon [16].

3.1.2. Initial state: standalone mode (Standalone GPS)

The initial data stream was a standard set of NMEA 0183 protocol messages, compliant with the IEC 61162-1 standard [17]

```
$GPGGA,152244.00,4625.3849,N,03044.5206,E,1,09,01.3,0041,M,
0031,M,,*65 $GPGNS,152243.00,4625.3849, N,03044.5206,
E,A,09,01.3,0041,0031,,*09.
```

Analysis of key indicators:

- *positioning mode*: Fix Quality field in the $GPGGA message has a value of 1, which clearly corresponds to a standalone solution (Standalone GPS);
- *mode indicator*: Mode Indicator field in the $GPGNS message has a value of A (Autonomous), confirming the standalone status.

3.1.3. Activation of DGPS mode and analysis of contradictions

After manually activating DGPS mode via the user menu, the receiver began to broadcast the following set of messages

```
$GPGGA,180047.00,4625.3835, N,03044.5275,E,2,10,01.2,0054,
M,0031,M,999,*53 $GPGNS,180047.00,4625.3835,N,03044. 5275,
E,D,10,01.2,0054,0031,999,*3E $GPRMC,180047.00,A,4625.3835,
N,03044.5275,E,00.0,021.8,170822,,, D*6A.
```

Analysis of this data stream revealed a fundamental inconsistency: although the values Fix Quality = 2 and Mode = D formally indicate operation in differential correction mode, the value 999 in the correction age field (diffAge) clearly indicates that the receiver is not receiving current DGPS corrections.

In weak signal conditions, the situation only gets worse. During the experiment, with the antenna partially shielded, the receiver generated the following repeating message

```
$GPGNS,182251.00,4625.3056,N,03044.2063,E,D,03,11.5,
0041,0031,999,*05.
```

Analysis of this message shows the absurdity of the receiver's indication logic: it continues to indicate differential mode (D) when there are only 3 visible satellites (numSV = 3) and a catastrophically high HDOP value (11.5), which makes even basic 2D coordinate determination impossible.

The results of the experiment confirm that the outdated Samyung SPR-1400 receiver provides unreliable information about its operation in differential mode. The reason for this behavior is that the decision to indicate the mode is made solely on the basis of a single setting, rather than on the fact of receiving corrections and using them. As a result, an adjacent system (e. g., AIS transponder), analyzing only the D flag or indicator 2, will systematically broadcast false information about its location with high accuracy, thereby creating a direct threat to the safety of navigation.

3.2. Impact of new standards on solving the problem and research into modern receivers

The problem described above with false indications on outdated equipment can certainly be classified as a systemic risk.

The new unified international standard IEC 61108-7:2024 [18] regulates the operation of shipborne GNSS receivers with SBAS L1. The full name of the standard, "Maritime navigation and radiocommunication equipment and systems – Global navigation satellite systems (GNSS) – Part 7: Shipborne SBAS receiver L1" clearly indicates its specialization. The purpose of implementing the standard is stated as: ensuring the safe and coordinated use of SBAS by all shipborne receivers worldwide at harbor entrances/approaches and in ocean/coastal waters.

The standard requires receivers to provide more detailed information about the status of correction signal processing [19]. It does not simply suggest, but obliges equipment manufacturers to provide users and related systems with a clear and unambiguous assessment of not only the accuracy, but also the integrity of the navigation solution. Integrity in the context of SBAS is a measure of confidence in the information transmitted by the system. SBAS continuously monitors the "health" of each GNSS satellite. If the signal from a satellite becomes unreliable, SBAS notifies users almost instantly, allowing them to exclude that satellite from their calculations.

A key innovation of the standard is the requirement to output extended NMEA messages, such as $__GFA (SBAS-specific status), and the addition of a Navigational Status field to existing messages (e. g., $GNGNS). This field can take the values: SAFE, CAUTION, or UNSAFE, reflecting the final integrity assessment based on SBAS data.

Now, even in cases where the receiver receives and uses differential corrections (determining position with high accuracy), but the signal integrity is compromised, it is required to report this with the UNSAFE or CAUTION flag.

The innovations described will undoubtedly increase the reliability and informativeness of navigation data. However, in the authors' opinion, it is not at all obvious that the use of new-generation receivers that meet these requirements will have a positive impact on solving the problem of ambiguity in the indication of the receiver's differential mode of operation. This uncertainty prompted the authors to conduct further experimental research.

3.3. Study of the u-blox NEO-F10N receiver

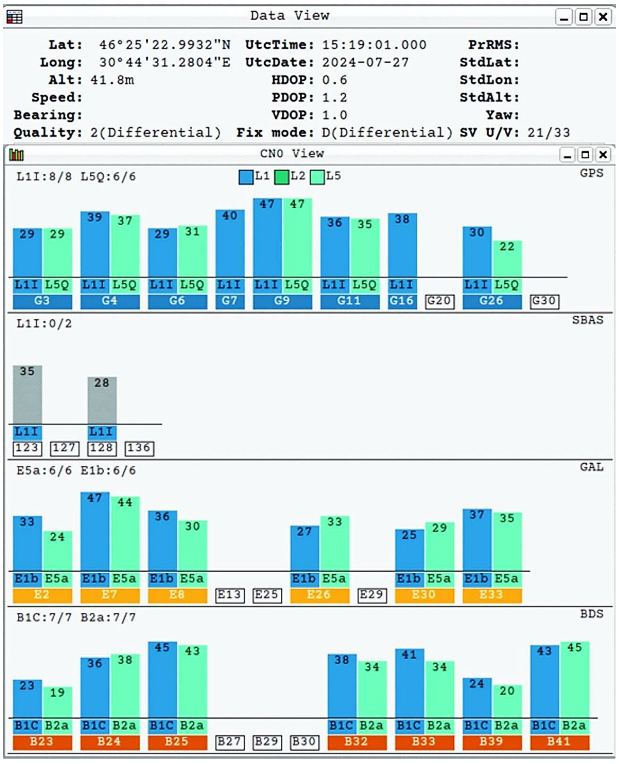
According to its specifications, the u-blox NEO-F10N multi-frequency and multi-system GNSS receiver module is capable of receiving and processing SBAS L1C/A signals, including EGNOS [20].

Analysis of NMEA logs from the modern u-blox NEO-F10N multi-system receiver showed the following result, which at first glance seems paradoxical, but is actually logical and fully consistent with the spirit of the new standard.

It is worth noting that leading manufacturers, such as u-blox, often incorporate functional elements into their modules that meet the requirements of new international standards even before a specific product is formally certified to that standard. This is a common practice that allows them to bring advanced features to the market. For example, u-blox implements SBAS integrity support at the level of built-in RAIM algorithms and adds a navigation status field to standard NMEA messages, which de facto complies with the requirements of IEC 61108-7, even if the receiver is not formally certified [21].

Let's consider a typical set of messages received from this receiver and their decryption using specialized software [22], as shown in Fig. 2

```
$GNGGA,151901.00,4625.38322,N,03044.52134,E,2,12,0.60,41.8,M,30.3,M,,*7B
$GNGNS,151901.00,4625.38322,N,03044.52134,E,DNDDNN,21,0.60,41.8,30.3,,,V*22
$GNGBS,151901.00,1.2,1.1,2.9,14,,20.4,1001.6,1,3*5D.
```



```
Data View
     Lat:  46°25'22.9932"N  UtcTime: 15:19:01.000       PrRMS:
    Long:  30°44'31.2804"E  UtcDate: 2024-07-27        StdLat:
     Alt: 41.8m                HDOP: 0.6               StdLon:
   Speed:                      PDOP: 1.2               StdAlt:
 Bearing:                      VDOP: 1.0                  Yaw:
 Quality: 2(Differential)  Fix mode: D(Differential) SV U/V: 21/33
```

Fig. 2. Decoding of navigation data
from the u-blox NEO-F10N module output

Analysis:

– $GNGGA with quality indicator 2 and $GNGNS with mode DNDDNN indicate that the receiver calculates the position taking into account differential corrections for the GPS, Galileo, and BeiDou systems, which signals it receives;

– however, at the end of the $GNGNNS message, there is a navigation status flag V (Void/Unsafe), which, according to the logic laid down in the IEC 61108-7:2024 standard, means that the solution is considered unreliable/unsafe;

– the reason for this becomes clear when analyzing the $GNGBS message: the receiver's internal integrity monitoring system (RAIM) detected a fault in the satellite with PRN 14 (failedSvId field), estimating its measurement offset at 20.4 meters.

This result clearly demonstrates the operation of a modern receiver, which separates the concepts of accuracy and integrity, in accordance with the requirements of the new standards. The receiver can mathematically calculate a highly accurate differential solution, but if its internal integrity monitoring system (RAIM) detects a problem (in this case, a faulty satellite), it must mark this solution as dangerous (V flag).

Thus, the solution to the problem of reliably eliminating false indications has now reached a new level and requires a review of the algorithms for the operation of related equipment, for which it is necessary to conduct a comprehensive analysis not only of the mode flags, but also of the integrity status.

3.4. Investigation of the u-blox ZED-F9P receiver: Complex contradictions

An even more complex picture emerges from the data obtained during the experiment with the u-blox ZED-F9P multi-frequency and multi-system GNSS receiver module (MSR) (Fig. 1), which also supports the reception and processing of SBAS L1C/A signals [23].

For testing purposes, the receiver was allowed to process all available navigation signals (Fig. 3).

Here are some excerpts from the log files of its work

```
$GNGNS,120443.00,4625.37951,N,03044.53676,E,DDDD,30,0.51,40.6,30.3,,0000, V*29 $GNGGA,120443.00,4625.37951,N,03044.53676,E,2,12,0.51,40.6,M,30.3,M,,0000*7A
$GNGBS,120442.00,0.3,0.2,0.6,,,,,,*59.
```

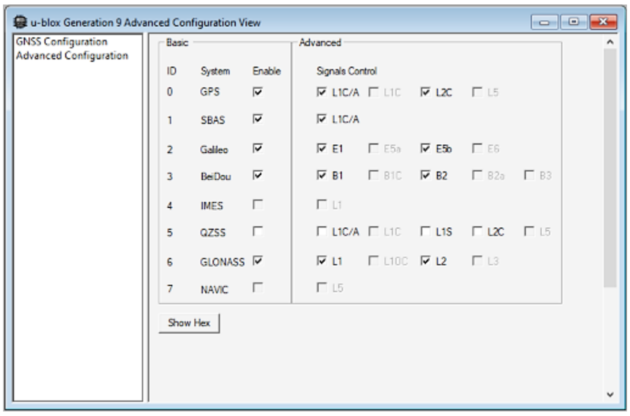
Their analysis showed the following:

– $GNGGA has a quality indicator of 2 (DGPS);

– $GNGNS shows DDDD mode, i. e., all systems are operating in differential mode (Fig. 4);

– $GNGBS reports very low expected errors (0.3 m in latitude, 0.2 m in longitude), which is typical for high-precision mode;

– DOP factors have excellent values (HDOP = 0.51).



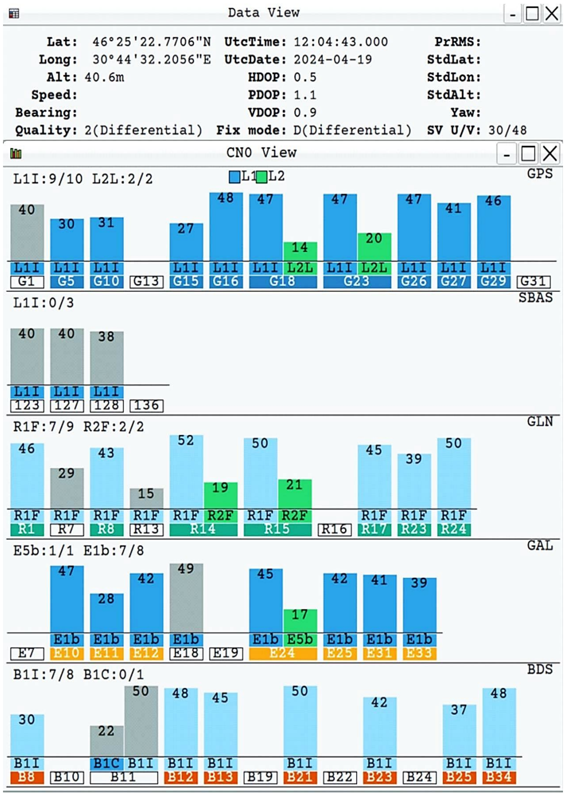
u-blox Generation 9 Advanced Configuration View

GNSS Configuration
Advanced Configuration

Basic / Advanced

ID	System	Enable	Signals Control				
0	GPS	☑	☑ L1C/A	☐ L1C	☑ L2C	☐ L5	
1	SBAS	☑	☑ L1C/A				
2	Galileo	☑	☑ E1	☐ E5a	☑ E5b	☐ E6	
3	BeiDou	☑	☑ B1	☐ B1C	☑ B2	☐ B2a	☐ B3
4	IMES	☐	☐ L1				
5	QZSS	☐	☐ L1C/A	☐ L1C	☐ L1S	☐ L2C	☐ L5
6	GLONASS	☑	☑ L1	☐ L1OC	☑ L2	☐ L3	
7	NAVIC	☐	☐ L5				

Fig. 3. Configuration of the MSR U-blox ZED-F9P for testing



```
Data View
     Lat:  46°25'22.7706"N  UtcTime: 12:04:43.000       PrRMS:
    Long:  30°44'32.2056"E  UtcDate: 2024-04-19        StdLat:
     Alt: 40.6m                HDOP: 0.5               StdLon:
   Speed:                      PDOP: 1.1               StdAlt:
 Bearing:                      VDOP: 0.9                  Yaw:
 Quality: 2(Differential)  Fix mode: D(Differential) SV U/V: 30/48
```

Fig. 4. Decoding of navigation data
from the output of the U-blox ZED-F9P module

All these data convincingly indicate reliable operation in SBAS mode. However, at the same time, the $GNRMC and $GNGNS messages contain a V (Void/Warning) flag in the navigation status field, equivalent to UNSAFE, which means that the data is invalid or unreliable.

This creates a fundamental paradox: the receiver indicates a successful location calculation taking into account differential corrections, but its internal integrity control system marks this solution as dangerous. This indicates that "differential mode" is not a simple binary "on/off" state, but a complex status that includes not only accuracy but also integrity, which can be compromised even when accuracy criteria are formally met.

A summary of the results of the studies conducted allows to conclude that there is a two-level problem in the indication of differential mode.

3.5. Uncertainties on board the vessel

According to current IMO regulations, on-board navigation equipment (ECDIS, AIS, VDR, autopilot, etc.) must use positioning data received via NMEA 0183/IEC 61162-1 from the main GNSS receiver [3]. This means that the operator on the bridge may see the "DGPS" or "Differential" indicator, but cannot be sure that differential corrections are actually being used to obtain a position with a high accuracy status. As shown above, this could be either a real high-accuracy mode with confirmed integrity, a false flag from an outdated receiver, or a differential mode with compromised integrity from a modern receiver.

3.6. Uncertainties in automatic transmission via AIS

The ship's AIS transponder must periodically broadcast reports on its location, indicating the accuracy of its determination, which is represented by the Position Accuracy bit. However, like other onboard navigation equipment that meets current requirements, it does not have complex analysis logic and relies on primitive flags in navigation messages from the onboard GNSS receiver.

A key contradiction arises from the discrepancy between the requirements of the standards for flag accounting:

- ITU-R M.1371-5 defines the Position Accuracy bit as 1 if the position error is ≤ 10 m (95% probability) or if the ship's GNSS receiver connected to the AIS transponder indicates operation in differential mode. The document does not require consideration of GNSS integrity status [24];
- IEC 61993-2:2018 adds a requirement to consider not only accuracy but also integrity, referring to the need to obtain a navigation status flag from GNSS [25].

A modern GNSS receiver that complies with IEC 61108-7 correctly transmits the V flag (invalid/dangerous). However, an AIS transponder following the older ITU specification may ignore this integrity flag and, relying only on the D or 2 flags, set the Position Accuracy bit to 1, transmitting false confidence in accuracy. This creates a system conflict where some devices will correctly lower the accuracy status, while others will not. As a result, data with an unknown and potentially unreliable accuracy assessment will enter the unified AIS information exchange system, creating a systemic risk to navigation safety.

3.7. Development of proposals for solving the problem

3.7.1. For developers of ship equipment (AIS, EKNIS)

The algorithms for analyzing and processing GNSS data should be revised. The high accuracy flag (e. g., Position Accuracy in AIS) should only be transmitted if the following conditions are met:

- the quality indicator in $GNGGA is equal to 2;
- posMode in $GNGNS contains the D flag;
- diffAge in $GPGNS or $GPGGA has a low value;
- the navigation status in $GNRMC/$GNGNS (if present) is not equal to V (Void/Unsafe);
- the receiver does not explicitly signal integrity problems in $GNGBS or $__GFA.

This rule can be expressed using a logical function that determines the position accuracy (PA) flag based on the position sensor (PS) status, the RAIM (R) flag, and the NavStatus (N) flag

$$\mathrm{PA} = (\mathrm{N} \neq \mathrm{UNSAFE}) \wedge ((\mathrm{PS} \in \{1, 2, 3\}) \vee ((\mathrm{PS} = 4) \wedge (\mathrm{R} = 1))), \quad (1)$$

where PS is the position sensor status, which can take values from 1 to 6, according to the document *Position sensor fallback conditions* [25]. Values 1–3 mean different options for obtaining differential correction; 4–5 mean operation without correction; 6 – dead reckoning mode. R – RAIM flag (1 – RAIM is working; 0 – not working). PA – accuracy flag (1 – high accuracy; 0 – low). N – NavStatus flag (can take values SAFE, CAUTION, UNSAFE).

3.7.2. For IMO and ITU

It is necessary to initiate a revision of ITU-R M.1371 standard, taking into account the modern understanding of integrity. In particular, it is proposed to change the rules for setting the Position Accuracy bit value by adding an explicit requirement to take into account the Navigational Status flag from the GNSS receiver.

3.7.3. For navigators and technical specialists

It is necessary to develop an understanding that the "DGPS" indicator on the display is not an absolute guarantee that the receiver is actually operating in differential mode. When performing critical operations, the status of the receiver should be checked using its service software (e. g., u-center for u-blox), which provides comprehensive information about its internal state.

3.8. Limitations of the study and directions for further development

The implementation of the proposed solutions faces a number of significant limitations related to the existing fleet of ship equipment and certification requirements. These limitations are listed below.

- *Incompatibility with older equipment.* The results obtained cannot be applied to ships equipped with outdated navigation equipment. To generate NavStatus flags (SAFE, CAUTION, UNSAFE), it is necessary to use ship receivers that comply with the new IEC 61108-7:2024 standard. The old equipment fleet does not support this standard, which makes it incapable of processing and transmitting this data.
- *Delays related to certification.* The introduction of new equipment will be a lengthy process. Only certified navigation equipment is allowed to be used on ships. This requirement significantly delays the replacement and modernization process, as each new device must be tested for compliance with maritime standards.
- *Modernization of AIS transponder software.* The implementation of the logical function PA = f(PS, R, N) (1) requires an update of the software (SW) of ship AIS transponders. This is possible, but it involves a large-scale campaign to modernize the software on ships, which also requires time and resources.

Areas for further research could include:

- conducting comparative tests of a wide range of certified marine GNSS receivers from different manufacturers to create a catalog of their behavior in indicating differential mode;
- studying the practical impact of the implementation on the new generation of ship navigation equipment according to IEC 61108-7 standard;
- quantitative analysis of AIS data in areas covered by EGNOS to assess the frequency of high-precision flag transmission and compare it with the actual availability and integrity of EGNOS signals.

4. Conclusions

The study revealed a number of systemic problems in the field of indicating the operating mode of ship GNSS receivers:

- indicating operation in differential mode via the standard NMEA 0183 protocol does not allow for unambiguous interpretation of the situation, which can lead to incorrect assessment of the accuracy of navigation data;

– outdated equipment may identify differential mode without applying corrections, misleading related systems;

– the ability to eliminate ambiguity in differential mode indication will allow navigators and coastal services to significantly improve the adequacy of decision-making – the error when using differential mode is 2–3 times less than when using autonomous mode.

Modern GNSS receivers correctly implement the requirements of IEC 61108-7 and signal integrity violations, but AIS transponders, in accordance with ITU logic, can ignore these warnings. This inconsistency must be eliminated to avoid the risk of false confidence in navigational safety.

Conflict of interest

The authors declare that they have no conflict of interest with respect to this research, in particular of a financial, personal, authorship, or other nature, that could influence the research and its results presented in this article.

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technology in the creation of this work.

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