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VERIFICATION OF THE AIS SERVICE AVAILABILITY MODEL BASED ON DYNAMIC DATA STREAMS RECORDED FROM THREE RECEIVING STATIONS IN THE POLISH COASTAL AREA

Krzysztof JASKÓLSKI[1], Wojciech CZAPLIŃSKI[2]

[1] *Polish Naval Academy, Faculty of Navigation and Naval Weapons, Gdynia, Poland*

[2] *Maritime University of Szczecin, Faculty of Computer Science and Telecommunications, Szczecin, Poland*

Abstract:

The reliability aspects of the operation of radio navigation systems constitute a crucial element for the safety of maritime navigation.. Technological progress in ship traffic monitoring is achieved through the design of ship systems and shore infrastructure equipped with Automatic Identification System (AIS) devices. One of the issues with AIS operation is the limited availability of the service in the form of data streams with an extended data age recorded on the receiving side. Another problem is the emission and reception by ships of incomplete positional reports without navigational parameters. Such situations render the system operationally unfit in terms of processed information. Therefore, it is essential to investigate the operational characteristics of radio navigation systems and develop tools to monitor the AIS service status on the receiving side. This article presents the development of a model for the availability of an AIS for vessels based on the determined mean time of the occurrence of incomplete navigation parameter values in AIS messages and the results of research in the domain of time and frequency using a mathematical method of the Fast Fourier Transform (FFT). The study results refer to six basic navigation parameters and show a varying service availability factor for the navigation parameters under study, i.e. the latitude (LAT), longitude (LON), speed over ground (SOG), course over ground (COG), heading (HDT), and the rate of turn (ROT). The data recorded by three receiving AIS stations on the Polish coast, i.e. PLKOL, PLSZZ, and PLSWI, were used as a key source of practical knowledge on the limitations of the AIS service availability. The experiment observed interruptions in the regular transmission of data from navigation equipment in the AIS service operational zone. As a result, the functional relationship was described based on the spectral analysis of the frequency of occurrence of times between the service repair (Time To Repair, TTR), and the model was proposed to be applied to the study of other variables. The presented model is a tool that allows for improving the monitoring of vessel traffic in terms of reliability, which directly affects the improvement of maritime traffic safety.

Keywords: *automatic identification system, reliability theory, fast Fourier transform, spectral analysis, digital signal processing*

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Contact:
1) k.jaskolski@amw.gdynia.pl [https://orcid.org/0000-0001-7156-2375] – corresponding author, 2) w.czaplinski@pm.szczecin.pl [https://orcid.org/ 0000-0002-9503-4742]

1. Introduction

The Automatic Identification System (AIS) is a key innovation in shipping safety. The aim of introducing the AIS system was to improve the observation of vessel movements, which was previously carried out via radar system. The transmission of information is carried out wirelessly in the very high frequency (VHF) band between AIS transponders. The source of the digital data exchange is the information originating from devices being part of the navigational equipment of a vessel. These devices include a positioning system receiver, a gyrocompass, and a rate-of-turn (ROT) indicator. All the devices are connected to the AIS transponder by a wire which is responsible for data collection and the transmission of compressed data via a digital radio communication system.

Navigational systems and shipboard equipment perform their task involving the determination of a specific navigation parameter that is affected by the measurement error, which characterizes the accuracy of the navigational system. The service provided by the navigational system is defined by operational characteristics in the area of system operation, including availability, continuity, integrity, reliability, and accuracy (Zalewski, 2020). Therefore, the following definitions necessary to understand the issues raised in the article were adopted:

Navigational system availability is the probability of the correct system operation at any moment with the required accuracy level in the area of system operation(Zalewski et al., 2022)(Helwig et al., 2018). It is the probability with which the service provided by the system is available to a user located within the zone of its operation (Department Of Defense USA., 2020)(Specht, 2021).

The navigational system operational zone is an area in the OXY plane in marine navigation in which the system enables the determination of a navigation parameter and the operation of the system according to its characteristics with the required accuracy level.

The automatic identification system does have certain shortcomings. One of the problems is the limitation of the availability of the service provided by AIS, manifesting itself as the occurrence of incomplete values of the data derived from the source navigation equipment. According to the AIS system Technical Recommendation ITU-R.M-1371, developed by the International Telecommunication Union (ITU), it is permissible for incomplete data to occur when input data are not transmitted to the AIS transponder. Incomplete data were marked with the "default" parameter. Such appearance of incomplete data in an AIS message results in a lack of complete information on the vessel equipped with an AIS transponder for system users receiving AIS data by radio. AIS information is used by maritime pilots and navigators under special navigational conditions, i.e. on port approach fairways, in harbors, narrow passages, and locks. Systems supporting the maritime pilot use AIS information and enable the planning and performance of maritime vessel maneuvers in areas where high accuracy of navigation parameters is required and there is a high risk of damage to the vessel or cargo. The AIS service availability is also of importance for the recording of traveler data by a voyage data recorder (VDR). One of the types of data recorded by this system is AIS information. In the event of a vessel failure, when the voyage data recorder is damaged, it is possible, with the smooth operation of the AIS transponder of this vessel, to reconstruct the voyage data of the vessel in distress based on the AIS data recorded by the VDR of another vessel located at a distance not exceeding the AIS radio range.

The problem of the correct operation of a navigational system has been addressed, e.g. by the International Maritime Organization (IMO) (IMO, 2017) and the International Association of Lighthouse Authorities (IALA) (IALA-AISM, 2018). As part of the improvement of safety, attention was paid to the operational characteristics of navigational systems, such as availability, continuity, and integrity. In addition, there are many studies published by researchers from research institutions and technical universities on the availability and integrity of the AIS service (Jaskólski et al., 2021) (Fournier et al., 2018) (Iphar et al., 2019) (Kessler, 2020) (Siegert et al., 2016) (Emmens et al., 2021) (Iphar et al., 2020).The current status of availability of the AIS service is presented, e.g. in a study by(Tu et al., 2018). The research results from the initial period of the AIS system operation are presented in studies by (Banyś et al., 2012) (Last et al., 2014) (Harati-Mokhtari et al., 2007) (S. J. Chang, 2004). The results of studies indicate the lack of AIS service availability in terms of the occurrence of incomplete data as early as the AIS system implementation stage. First of all, a high percentage of incomplete heading (HDT) and rate of turn (ROT) values can be observed. The frequency of occurrence of incomplete data for the remaining dynamic parameters, i.e. course over ground (COG), speed over ground (SOG), latitude (LAT), and longitude (LON), is definitely lower. This is particularly noticeable in marine areas, excluding anchorages and harbor areas.

The AIS service availability, as a feature referring to the determination of the age of complete data as well as the determination of moments of correct operation and failure of the AIS based on the occurrence of incomplete navigation parameter values, requires verification and a critical approach to previously conducted research. To this end, an AIS service availability model was developed based on the estimation of the mean time to repair (MTTR) for 21,480 samples lasting for 360 seconds, i.e. six minutes. The application of the spectral analysis of the time spent in the state of AIS service failure and the presentation of MTTR in the domain of frequency represent a new research approach in the theory of navigational system reliability(Jaskólski, 2022).

The article consists of an Introduction in which the problem associated with the limited availability of the AIS service is preliminarily presented, and the authors of previous research addressing the inadequacy of the AIS service are indicated. In the subsequent part of the article, Chapter 2 presents the aim and methodological assumptions of the presented research, choosing the method of conducting research, outlining the stages of research, and presenting the theses to be proven. In Chapter 3, a Literature Review is conducted, providing a review of related literature on the availability of the AIS service. Chapter 4, Materials and Methods, presents a description of the measurement experiment carried out at three AIS receiving stations located along the Polish coast. Navigational parameters of the positional report were determined based on which the age of dynamic data was identified. Initial assumptions for developing the AIS service availability model were presented, along with the structure of the model and the defined research object.

In the further part of Chapter 4, the methodology of presenting the amplitude spectrum of MTTR in the frequency domain is presented, using Fourier transform for this purpose. In Chapter 5, Results, an analysis of the research results is carried out based on the amplitude spectrum module of the signal in the frequency domain for the MTTR parameter determined based on incomplete data age and time series of MTTR for three AIS receiving stations on the Polish coast. The transition moments between service availability states were then determined. For each of the three receiving stations and for each navigational parameter, the intensity of transitions between states was presented, and service availability was determined.

In the Conclusions chapter, the hypotheses of the research are proven or rejected as stated in the introduction.

2. The aim and methodological assumptions of the presented study

One of the problems with the functioning of the AIS service is the occurrence of incomplete data in streams indexed by the MMSI number (Šakan et al., 2018). Incomplete data originates from the navigational devices coupled with the AIS transponder. The International Telecommunication Union (ITU) allows for such a situation when certain navigational parameters are transmitted in binary form to the AIS transponder. Default values are predefined for software variables if the system user does not specify the values of these variables. The occurrence of incomplete data in data streams renders information about the vessel unavailable to users receiving AIS data via radio, directly impacting navigation safety. (Alessandrini et al., 2019) and the identification of vessel traffic anomalies in the event of a piracy attack.(Mazzarella et al., 2015) (Papi et al., 2015). Additionally, reliable and available AIS data can be used for estimating the vessel's position and studying the ship's speed relative to the intensity of vessel traffic. (Kang et al., 2018) (Kang et al., 2019)

The study of the availability of dynamic AIS data is associated with a growing problem of GPS system falsification (spoofing) and jamming observed in recent years.

Therefore, the utilitarian goal of the article is to develop a model of AIS service availability based on the occurrence of AIS messages containing incomplete navigational parameter data, and to specify which parameters and why they have an impact on the incompleteness of the AIS service.

The problem of modelling the AIS service availability and integrity is an issue of relevance to navigation safety(Gao et al., 2018)(Last et al., 2015).

In the context of estimating the AIS service availability and integrity, the studies published to date considered the following research methods for navigation systems:

A. Stochastic methods using Markow and semi-Markov processes– mathematical methods that enable the description and investigation of real random processes. These represent an important class of stochastic processes that allow changes in quantities over time to be described mathematically(Specht & Rudnicki, 2016b)(Salnikov et al., 2016).
B. Model based on the chi-square test, presented in (Siegert et al., 2016).The chi-square test is used for testing hypotheses. The test value is assessed using the chi-square distribution. This test is most commonly used in practice and can be used for the testing of compatibility of both measurable and non-measurable characteristics.
C. Generalized likelihood ratio (GLR) – a control method for detecting changes in system parameters for individual observations. The method is usually applied in the system for monitoring the object under study. It is based on determining n observations from the sample at each time interval, where n is sufficiently large for the regression model to be fitted at each time interval using n observations (Y. Chang & Chen, 2020) (Abba et al., 2019).
D. Unidirectional neural networks– referred to as perceptrons. In networks of this type, neurons are organised into layers, among which an input layer and an output layer can be distinguished. The others are called hidden layers. The concept of using artificial neural networks for system diagnosis involves the construction of a neural classifier of the states of an object. A properly trained neural network is expected to classify the state of the system into the appropriate malfunction groups (Jwo et al., 2023).

In order for an object to be reliably navigated, it should be based on credible and available data streams derived from shipboard systems and equipment. Therefore, to solve the problem, tools need to be developed to identify the state of availability of shipboard equipment and systems (Siegert et al., 2016)(Specht & Rudnicki, 2016b)(Rudnicki, 2015)(Specht, 2021).

This article presents a study that aims to develop a probabilistic model for analysing the availability and integrity of AIS services. The study will also examine instances where the system's dynamic data exceeds its permissible age and present the amplitude spectrum of service failure time. Lastly, the practical application of this model will be demonstrated in the Polish coastal area.

In order to achieve the research objectives formulated in this way, the following tasks had to be completed:

A. The development of an AIS service availability model based on the age of dynamic data.
B. The determination of moments of the correct operation and failure of the AIS service based on the proposed service availability model.
C. The determination of the frequency of service failures in samples using Fast Fourier Transform (FFT) and the presentation of the study results using the amplitude spectrum of the mean time to repair (MTTR) in the domain of frequency to this end.
D. The determination of the probability of the AIS service being in the failure state and a state of correct operation.

Where:

A. The age of dynamic data is the interval between sequentially received position reports indexed by the MMSI number in relation to the selected navigational parameter: COG, SOG, HDT, ROT, LAT, LON.
B. The permissible age of dynamic data is the interval between sequentially received positional reports indexed by the MMSI number with respect to the selected navigational parameter: COG, SOG, HDT, ROT, LAT, LON, whose content corresponds to the value presented in positional reports defined in the AIS technical specification: ITU-R.M. 1371.
C. Incomplete data refers to AIS data whose content does not match the content of messages defined in the AIS technical specification: ITU-R.M. 1371.
D. Time to Repair (TTR) is the time when the content of a positional report indexed by MMSI in relation to the selected navigation parameter: COG, SOG, HDT, ROT, LAT, LON, assumes a "default" value and is inconsistent with the value of complete data presented in positional reports defined in the AIS technical specification: ITU-R.M. 1371.

E. Time to Failure (TTF) is the time when the content of a positional report indexed by MMSI in relation to the selected navigation parameter: COG, SOG, HDT, ROT, LAT, LON, assumes a value other than "default" and is consistent with the value of complete data presented in positional reports defined in the AIS technical specification: ITU-R.M. 1371.

The values of TTR and TTF for each data stream indexed by MMSI number, for the selected navigation parameter: COG, SOG, HDT, ROT, LAT, LON, were determined for every 360 s.

Hence, the research objective presented in this study is as follows:

The development of a probabilistic model for the availability and integrity of the AIS service, intended for the analysis of exceeding the permissible age of dynamic data in the system, along with the presentation of the amplitude spectrum of service failure and its practical application in the area of the Polish coast.

In order to conduct the proposed study and meet the state objective, it was adopted that the AIS service availability, as a feature referring to the determination of the age of complete data as well as the determination of moments of correct operation and failure of the AIS based on the occurrence of incomplete navigation parameter values, requires verification and a critical approach to previously conducted research. In view of the above, the following thesis was put forward:

A. Fast Fourier transform is a convenient mathematical tool presenting the amplitude spectrum of the dynamic data age thus determining the Time To Repair (TTR) of a selected navigation parameter coming from m data streams indexed by the MMSI number.
B. The availability of the AIS service depends on the dynamic data age of p navigation parameter indexed with MMSI numbers assigned to AIS transmitting and receiving devices in the system operation zone.
C. The availability of the AIS service determined on the basis of the age of dynamic data from 3 receiving stations on the Polish coast (Kolobrzeg, Swinoujscie, Szczecin) has values similar to each other and does not differ from the availability of the AIS service determined in an earlier period for other areas of the Polish coast.

The application of the spectral analysis of the time spent in the state of AIS service failure and the presentation of MTTR in the domain of frequency represent a new research approach in the theory of navigational system reliability.

The concept adopted in the article was realised in accordance with the research aim presented above.

3. Literature review

Despite the promising development of AIS, the system has many limitations (Šakan et al., 2018). The reliability and availability of the AIS service are operational characteristics of the system, the determination of which allows estimating the degree of proper utilization of AIS dynamic data streams in applications for maritime pilot support, piracy combat, and marine environmental protection. Although there is a recognized need to reduce factors causing limitations in AIS service availability and reliability, there have been few studies in this area. The types of factors causing limitations in AIS service availability have not been clearly defined. (Šakan et al., 2018). One of the key problems in the functioning of AIS is the difficulty in gathering reliable and timely information. The availability of the AIS service is linked, among other factors, to the radio range of AIS devices operating in the VHF band. AIS data can be noisy and incomplete. Considering all these factors, there is a need to investigate the limitations of AIS service availability. The results of the study on AIS service availability and reliability help better apply AIS data packages in various applications supporting navigation safety. Therefore, there is a need to acquire AIS data beyond the radio horizon of the VHF band (Alessandrini et al., 2019).

Most researchers either ignore the issue of AIS service availability or briefly state that such limitations exist. The authors of the article (Kang et al., 2019) developed methods for filtering AIS data to eliminate noise appearing in positional reports. Limitations in the availability of the AIS service lead to acquiring incomplete data with extended dynamic data age, consequently resulting in the interpretation of incomplete ship movement trajectories (Mazzarella et al., 2017) (Papi et al., 2015). There is a positive correlation between the intensity of ship traffic and the detection and tracking of a vessel using the AIS system (Kazimierski, W., Stateczny, 2015). Many transmissions in the same area can lead to message collisions, which are associated with limitations arising from the system's capacity. This causes limitations in the transmission of AIS data streams indexed by the MMSI number (Greidanus et al., 2016) (Last et al., 2015). Radio wave propagation conditions in the VHF band are of significant importance for ensuring the availability of the AIS service. Radio wave refraction causes limitations in the radio range of the system and disrupts the transmission of AIS data streams (Last et al., 2015) (Pelich et al., 2015). The concept of "black holes" presented in the article (Salmon et al., 2016) refers to the identification of areas with limitations in AIS service availability, where issues with the transmission of AIS data streams related to the radio range of the system occur. The authors present a hybrid approach to detecting AIS (Automatic Identification System) service availability constraints, which includes the following stages:

A. Offline mode for detecting black holes: This process involves identifying areas where AIS service availability is limited by examining historical data.
B. Online process aimed at categorizing cells and identifying cells with limited AIS service availability: This stage identifies cells that have recorded ship positions and determines whether AIS service availability in a given area meets the required level. It combines information from stages 1 and 2 to find areas not covered by the system's reach. (Kontopoulos et al., 2018).

Such studies indicate the inadequacy of the system in terms of information processing. Therefore, it is crucial to investigate the operational characteristics of radio navigation systems and develop tools for monitoring the state of the AIS service.

4. Materials and methods

The proper functioning of navigation, radio navigation, and radio communication systems is one of the elements to ensure the safety of maritime navigation. The problem of the correct functioning of navigation systems concerns both merchant marine vessels and warships and the effective monitoring of surface unmanned vehicles along a designated route. High technological advances have contributed to the development of equipment for vessels and unmanned vehicles that are equipped with AIS transponders. One of the problems of AIS operation is the limited availability of the service, manifested by the existence of incomplete values of radio-transmitted navigation parameters compressed in dynamic messages. This renders the system information unusable by vessels equipped with an AIS transponder.

The article presents the development of an AIS service availability model based on the determined mean time of the occurrence of incomplete navigation parameter values in AIS messages and the results of research in the domain of time and frequency using a mathematical method of the FFT. The study results refer to six basic navigation parameters. The data recorded by the AIS system ground stations located in Kołobrzeg, Szczecin, and Świnoujście were used as a key source of practical knowledge on the limitations of the AIS service availability (Fig. 1).

The experiment observed interruptions in the regular flow of data from the navigation equipment. As a result, the functional relationship was described based on the spectral analysis of the frequency of TTR occurrence, and the model was proposed to be applied to the study of other variables.

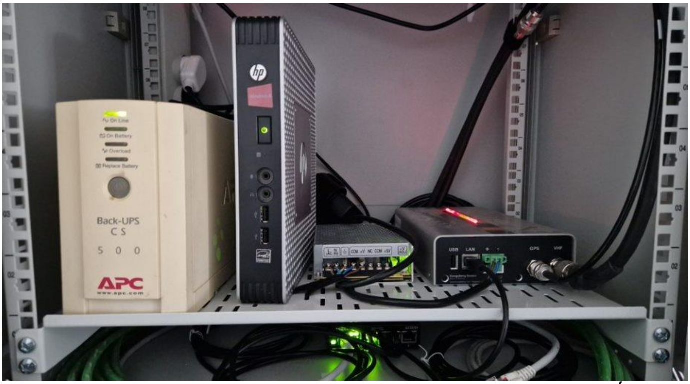


Fig. 1. Receiving station server recording dynamic data streams in Kołobrzeg and Świnoujście (own source)

4.1. Initial assumptions for the AIS service dynamic data stream availability model

The dynamic information of the AIS system represents the content of position reports, i.e. messages No 1, 2 and 3 when using A-class transponders mounted on conventional vessels. A stream of dynamic data contained in position reports is indexed with MMSI. If incomplete data appears in a single data stream indexed with an MMSI number, the technical specification of the ITU-R.M.1371 system recommends that these data be marked with default values that are used where actual navigation parameters are not available. Where the data is incomplete, the technical specification of the system recommends using the default values listed in Table 1.

Table 1. The values used in case of incomplete dynamic data contained in AIS position reports transmitted by A-class transponders (ITU, 2014).

Navigation parameter	Incomplete value
latitude	91
longitude	181
COG	3600
SOG	1023
ROT	731
HDT	511

When incomplete data contained in Table 1 appear in the content of an AIS message, it should be recognised that the AIS service availability was limited by a single, incomplete data stream indexed with an MMSI number.

It was assumed that each object equipped with an A-class AIS transponder transmitted position reports indexed with an MMSI number with an interval of 2-180 seconds would be regarded as an independent data stream. The number of data streams will be defined by the number of vessels equipped with an A-class AIS transponder located within the range of the AIS radio receiver coupled to a data recorder. In order to estimate the AIS service availability, dynamic data streams indexed with an MMSI number, which may contain incomplete dynamic data, were used. The occurrence of incomplete data fundamentally extends the age of the data, which critically affects the AIS system availability and increases TTR. Based on TTR and on the data streams indexed with an MMSI number, the mean time to repair (MTTR) and the AIS service availability factor A(t) will be determined.

4.2. AIS service availability based on the age of dynamic data

A navigation system failure can be considered as a condition where the system does not meet the established requirements for its intended use. This means that a system failure can be considered as a state that results from a failure of the system's internal or external components, e.g. a failure of the radio link (a high noise level in relation to the usable signal level). A service failure is a state in which the age of data can be equated with the occurrence of incomplete data in AIS position reports indexed with an MMSI number. Such a state of the system can be referred to as TTR (Specht & Rudnicki, 2016a). According to (Jaskólski, 2022), a mean TTR value can be applied to estimate service availability.

$$A = \frac{MTBF}{MTBF + MTTR} \qquad (1)$$

where:
MTBF – mean time between failures;
MTTR – mean time to repair.

If we consider the navigational structure of the system as an object that carries out its tasks over time, then the course of the operational process of the system in question comprises alternating periods of the object fitness $T_1, T_2, T_3, \ldots T_n$ understood as the duration of correct operation, and periods of unfitness $\eta_1, \eta_2, \eta_3, \ldots \eta_n$ understood as the duration of repair (renewal). Moments $t'_r = T_1 + \eta_1 + T_2 + \eta_2 + \ldots + T_{r-1} + \eta_{r-1} + T_r$ are referred to as system damage moments, while moments $t''_r = t'_r + \eta_r$ are referred to as system repair moments (Felski et al., 2015). It was assumed that time segments T_n and η_n are independent, positive random variables with known probability distributions. The operational state is assigned to binary 1. The failure state is assigned to binary 0, and represents an extended age of dynamic data, resulting from the reception of incomplete data in a position report. This is equivalent to a longer-than-normative interval between successive received data packets. The availability of the service for each navigation parameters i.e. LAT, LON, COG, SOG, ROT, and HDT is determined with TTR for each stream of data indexed with an MMSI number, thus identifying the sender. On this basis, it is possible to determine MTTR for each navigation parameter indexed separately with an MMSI number. Based on the set m of data streams, it is possible to determine MTTR for six navigation parameters, i.e. the basic components of position reports. The age of data of the recorded navigation parameters is the time interval between successive received position reports in which the tested navigation parameter LAT, LON, COG, SOG, ROT, and HDT contains complete data consistent with the values provided in Table 2.

Table 2. The values used in case of complete dynamic data contained in AIS position reports transmitted by A-class transponders (ITU, 2014)

Navigation parameter	A complete value
latitude	[-90, 90]
longitude	[-180, 180]
COG	[0, 3599]
SOG	[0, 1022]
ROT	[-127, 127]
HDT	[0, 359]

For a single navigation parameter (p) and a single data stream (m) indexed with an MMSI number, the MTBF value is calculated in accordance with the following relationship:

$$\mathrm{MTBF} = \frac{\mathrm{T_1 + T_2 + T_3 + \ldots + T_n}}{\mathrm{n}} \tag{2}$$

On the other hand, the *MTTR* value is determined in accordance with the following formula:

$$\mathrm{MTTR} = \frac{\eta_1 + \eta_2 + \eta_3 + \ldots + \eta_n}{\mathrm{n}} \tag{3}$$

Assuming that at any moment, the AIS system structure assumes the occurrence of m independent data streams indexed with an MMSI number, then $MTTR_{1,m}$ for the system navigational parameter $p = 1$ will amount to:

$$\mathrm{MTTR_{1,m}} = \frac{\mathrm{MTTR_{1,1} + MTTR_{1,2} + .. + MTTR_{1,M}}}{\mathrm{M}} \tag{4}$$

where:
$MTTR_{1,m}$ – mean time to repair for $m = 1..M$ streams of data indexed with an MMSI number for the selected navigation parameter $\mathrm{p} = 1$.

4.3. AIS service availability structure – defining the study object

The AIS service availability structure can be defined via the interval between two successively received position reports (message No 1, 2, 3), i.e. the age of data indexed with an MMSI number. To determine TTR at any moment, data indexed with an MMSI number value are used as a single data stream (sender-identifying information). To determine MTTR, the age of incomplete data is used as the expected value of the time spent in the failure state, calculated for M data streams for P navigation parameters. This will determine the state in which an object is found at any moment t. For two-state objects in terms of reliability, a reliability model is adopted in the form of two-state stochastic process $\mathrm{S_{(t)}}$, $\mathrm{t} \in [0, \tau\}$. It was initially assumed that $\mathrm{S_{(t)}}$ would be a binary representation of process availability.

$$\mathrm{S_{(t)}} = \begin{cases} 1 & \mathrm{t'}_{\mathrm{n+1}} \le \mathrm{t} < \mathrm{t''}_{\mathrm{n}} \\ 0 & \mathrm{t''}_{\mathrm{n}} < \mathrm{t} \le \mathrm{t'}_{\mathrm{n}} \end{cases} \tag{5}$$
for $\mathrm{n} = 0,1,2,\ldots \mathrm{N}$

where:
$\mathrm{S_{(t)}}$ – two-state stochastic process;
The state $\mathrm{S_{(t)}} = 1$ indicates that at moment t, the age of navigation parameter p dynamic data indexed with an MMSI number, is less than or equal to 10 s. For a six-minute interval = 360 s, MTBF≥342 s. The system is in the operational state (fit).
The state $\mathrm{S_{(t)}} = 0$ indicates that at moment t, the age of navigation parameter p dynamic data indexed with an MMSI number, is greater than 10 s. For a six-minutes interval = 360 s, MTTR>18 s. The system is in the state of failure (unfit).
For vessels moving at SOG ≥ of 22 knots, and vessels undergoing a course change with ROT > 5^0 over a time of 30 s, a dynamic data age alarm threshold of 10 s was adopted.
The proposed service availability structure based on the TTR quantisation process in samples lasting for six minutes of operation each allows the AIS system service to be classified into a specific operational state.

4.4. AIS dynamic data used in the modelling of AIS service availability

A single navigation message transmits six navigation parameters that can be written down as vector $\mathbf{x}_{p(t)}$.

$$\mathbf{x}_{p(t)} = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6]^T \tag{6}$$

where:
x_1 – LAT – latitude (WGS-84),
x_2 – LON – longitude (WGS-84),
x_3 – COG – course over ground,
x_4 – SOG – speed over ground.
x_5 – HDT– heading,
x_6 – ROT – rate of turn,
Dynamic data is indexed according to the MMSI number assigned to each AIS device. Therefore, the functional structure of the received AIS dynamic messages $\mathbf{\Phi}_{m_{x_p}}$ takes the following form:

$$\mathbf{\Phi}_{m_{x_p}} = \mathbf{\Phi}_{m(t)}[X_1 \quad X_2 \quad X_3 \quad X_4 \quad X_5 \quad X_6]^T, \quad m = \{1,2 \ldots M\} \tag{7}$$

where:
m – an index defining the number of data streams denoted by an MMSI number at time t.
X_p – a data set referring to the selected navigation parameter p indexed with an MMSI number
Assuming that the navigation parameters of vector $\mathbf{x}_{p(t)}$ are independent, the probability of receiving incomplete data can be described using the following relationship:

$$P_{\Phi_m(S_t=0)} = 1 - P_{\Phi_m(S_t=1)} = q_c = 1 - p_m, \tag{8}$$

where:
$P_{\Phi_m(S_t=0)}$ – probability of an event involving the system service being in state 0, i.e. the unfit state,
$P_{\Phi_m(S_t=1)}$ – probability of an event involving the system service being in state 1, i.e. the fit state,
p_m –probability of receiving complete data in a position report message,
q_c –probability of receiving incomplete data in a position report message.
The reception of navigation parameter p from the set P in m data streams from the set M, indexed with MMSI numbers, can be defined at moment t with the data set $X_{d(t)}$.

$$X_{d(t)} = [X_{p,m}] \tag{9}$$

Therefore, the reception of information from the set $X_{d(t)}$ for p={1…P} of navigation parameter with $m = \{1 \ldots M\}$ data streams takes the following form:

$$\xi_{n(t)} = [X_{1,1}X_{2,1}X_{3,1}X_{4,1}X_{5,1}X_{6,1}, \ldots, X_{1,m}X_{2,m}X_{3,m}X_{4,m}X_{5,m}X_{6,m}] \tag{10}$$

Assuming that the number of navigation parameters subjected to testing is p = 6, the service availability will be determined for each parameter separately, based on the data from m streams indexed with MMSI numbers, with an interval of six minutes.
Based on the data from AIS position reports indexed with MMSI numbers, MTTR was determined in each stream for each navigation parameter of vector $\mathbf{x}_p$.
Based on the TTR of a single navigation parameter determined for m data streams indexed with MMSI numbers, MTTR was estimated at the defined time t, and it was determined what state S {0,1} the system service was in.
For each navigation parameter, there is a possibility of specifying the frequency of the occurrence of a service failure. This task can be completed by using TTR spectral analysis in the domain of frequency. An analysis of changes in the service failure time in the domain of frequency can be presented when applying the FFT method.
This is a process in which the function under study is divided into parts. The result of this operation is the formation of an algorithm of Fourier transform that represents the unit effect of divided frequencies on the analysed function. The transform is responsible for converting the time form of the signal into frequency characteristics. The operator then obtains the periodic and frequency properties of the fragment being tested. Therefore, the described tool provides a basis for analysing and processing the functions being observed. The methods of signal analysis in the frequency domain are alternatively referred to as frequency or spectral methods. They enable easier characterisation of signal parameters as compared to temporal methods.

4.5. Amplitude spectrum of MTTR

Prior to starting spectral analysis of the signal in the frequency domain, MTTR needs to be determined in the first place in accordance with the relationships (3) and (4).Based on the data processed in this manner, a spectral analysis in the frequency domain was conducted for the MTTR oscillation(Yoo, 2019).

In order to assess the MTTR variability, a method for analysing the signal spectrum, i.e. frequency analysis known as Fourier transform, was proposed. Fourier transform involves the determination of the frequency of TTR occurrence, provided that the distribution in the time domain of the parameter under study is known. Fourier transform describes a signal in the frequency f or pulsation domain $\omega = 2\pi f$ (Rajaby & Sayedi, 2022).

The signal x_t can be represented using the inverse form of the Fourier transform in accordance with the following relationship:

$$x_t = \frac{1}{2\pi}\int_{-\infty}^{+\infty} x_\omega \cdot e^{j\omega t} d\omega, \tag{11}$$

where:
x_ω—Fourier transform for signal x_t
$e^{j\omega t}$ — exponential form of the harmonic wave

With the assumption described by relationship (11), Fourier transform of signal x_t can be determined according to the following relationship (Lin & Ye, 2019):

$$x_\omega = \int_{-\infty}^{+\infty} x_t \cdot e^{-j\omega t} dt, \tag{12}$$

In contrast to a continuous signal x_t, MTTR is referred to as a discrete signal x_i. The occurrence for signals of this type is represented by the following relationship(Ghani et al., 2020):

$$x_i = x_{i\Delta t}, \tag{13}$$

where:
$i = 0 \ldots N-1$.
N – number of observations.

The mathematical form of the signal is then written using the following relationship:

$$x_{(i)} = A_{(0)} + \sum_{r=1}^{\frac{N-1}{2}} A_{(r)} \cdot \cos\left[\omega'_{r_{(i)}} \cdot \Delta t + \varphi_{(r)}\right], \tag{14}$$

where:
$A_{(0)}$— main signal component;
A_r – signal harmonic component amplitude;
ω'_{r_i} – pulsation of the main signal harmonic component, where$r$ = 1;
φ_r – signal harmonic component phase.

Pulsation of the main signal harmonic components, where r = 1, takes the following form:

$$\omega' = \frac{2\pi}{N\Delta t}, \tag{15}$$

The form (20) of signal x_i informs for what values of distribution x_i the individual harmonic components r will be defined with an amplitude A_r, phase φ_r at any moment, in the domain of frequency, and the main component $A_{(0)}$.The notation is true for odd observations N. For an even number of observations N, the number of harmonic components$r$must fall within the range of $[1 \; \ldots \frac{N}{2}]$.

This relationship occurs for a finite number of observations. The mathematical methods assume the oddness of observations N.

4.6. Method for recording AIS dynamic data

The study on the AIS service availability for p=(1,…6) navigation parameters, and m=(1,…M) streams of data indexed with an MMSI number was carried out based on the recording of AIS data streams by three receivers located along the Polish coast. These include:

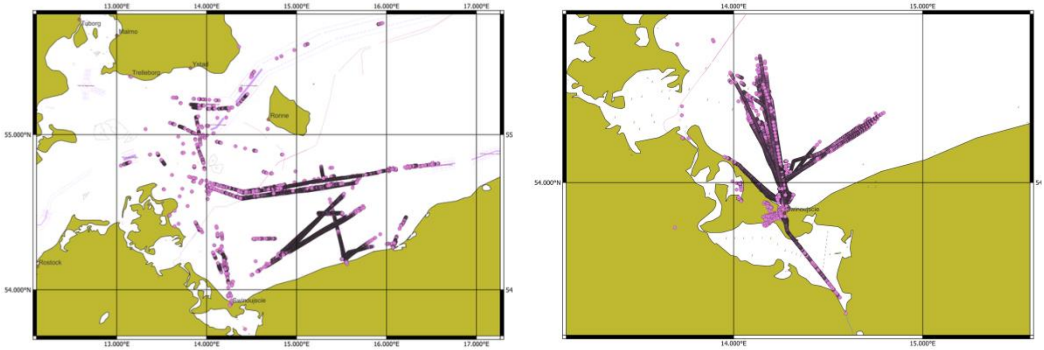
a. a PLKOL receiver located in Kołobrzeg, with an antenna on the roof of the Maritime University building (Maritime Training Centre in Kołobrzeg, ul. Mazowiecka 31-32),
b. a PLSWI receiver located in Świnoujście, with an antenna on the roof of the Maritime University building (Artists' Retreat, ul. Komandorska 5)
c. a PLSZZ receiver located in Szczecin, with an antenna on the roof of the Maritime University main building (ul. Wały Chrobrego 1/2 (Fig. 2, 3).

A data record in the form of 22,080 six-minute samples was acquired from receiving stations AIS PLKOL, PLSWI, and PLSZZ. Data recording was carried out from 00:00:00 CET on 01.11.2022 to 11:54:00 PM on 31.01.2023 (three months).

After encapsulation, the recorded data were stored in database files, and then queries were entered into the database based on the SQL language to filter the data and present the filtering results. The process of TTR time determination was carried out based on database data using the PostgreSQL application. The spectral analysis of TTR in the domain of frequency was performed using the MATLAB application.

5. Results and discussion

For the verification of the AIS service availability model, 104,545,683 position reports originating from A-class AIS transmitters, representing the equipment of vessels in accordance with the SOLAS Ch.V.19 convention, were used. The reports were recorded on servers coupled to three receivers located along the Polish coast: PLKOL, PLSWI, and PLSZZ. The recorded and filtered data were divided into 21,840 observations lasting 360 seconds each. If an object spends less than 360 seconds in the sector mentioned earlier, the service availability calculations will be based on the total time the object spent in the tested sector. This time should not exceed the duration declared in the study, and the data streams should be indexed with MMSI. The TTR of the AIS service for six-minute intervals from three ground stations on the Polish coast for navigation parameters LAT and LON is presented in Fig. 4 and 5.



(a) **(b)**

Fig. 2. Geographical positions of the AIS position messages received by the station (a) PLKOL (b) PLSWI

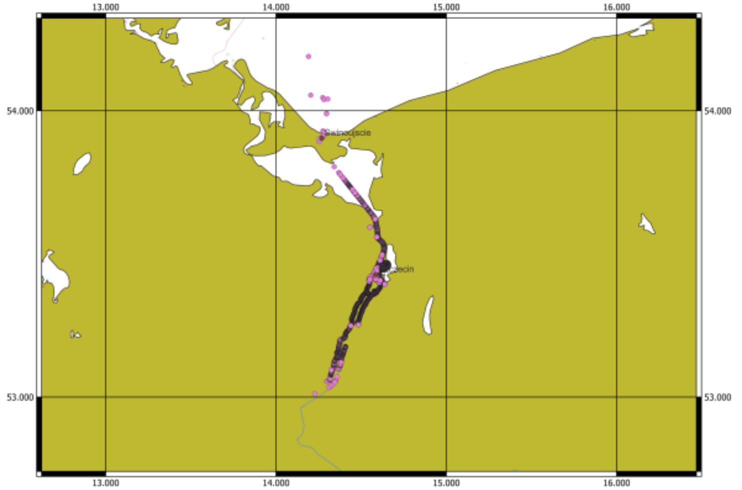
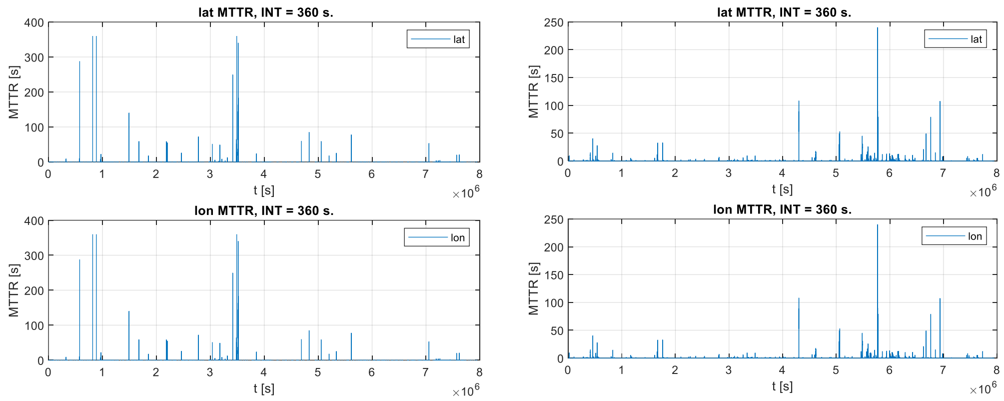


Fig. 3. Geographical positions of the AIS position messages received by the station PLSZZ



(a) **(b)**

Fig. 4. Mean time to repair based on the age of dynamic data at 360 s intervals for the parameters LAT and LON, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

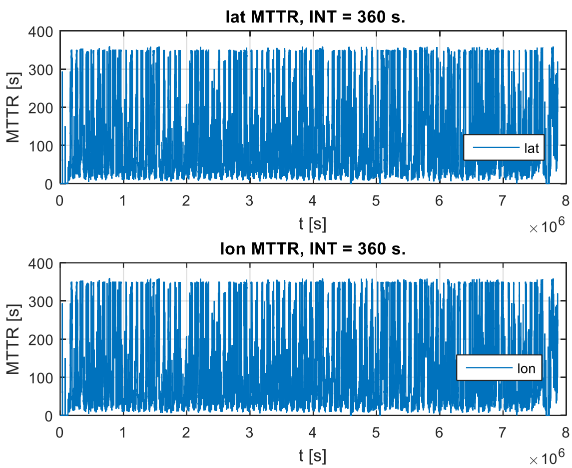


Fig. 5. Mean time to repair based on the age of dynamic data at 360 s intervals for the parameters LAT and LON, based on the dynamic data recorded by the station PLSZZ

The mean time between failures is the expected value of the time spent by the AIS service in the failure state for each p navigation parameter. The calculated TTR is the value necessary to determine the availability of the AIS service for the p navigation parameter. The MTTR determined for the LAT, LON parameter is five times the value of TTR = 360 s for dynamic data from the PLKOL station. There are occasional cases of exceeding the age of dynamic data here. The dynamic data age takes only once the TTR value of 230 s for the data recorded by the ground station PLSWI, in contrast to the data recorded by the ground station PLSZZ for 360 s samples. In view of the cruising area and the numerous moored vessels found there, the age of dynamic data, despite the adopted data analysis criterion for vessels with SOG $>$ 4 knots, takes values equal to the sampling period TTR = 360 seconds.

The MTTR of the AIS service for six-minute intervals from three ground stations on the Polish coast for navigation parameters COG and SOG is presented in Fig. 6 and 7.

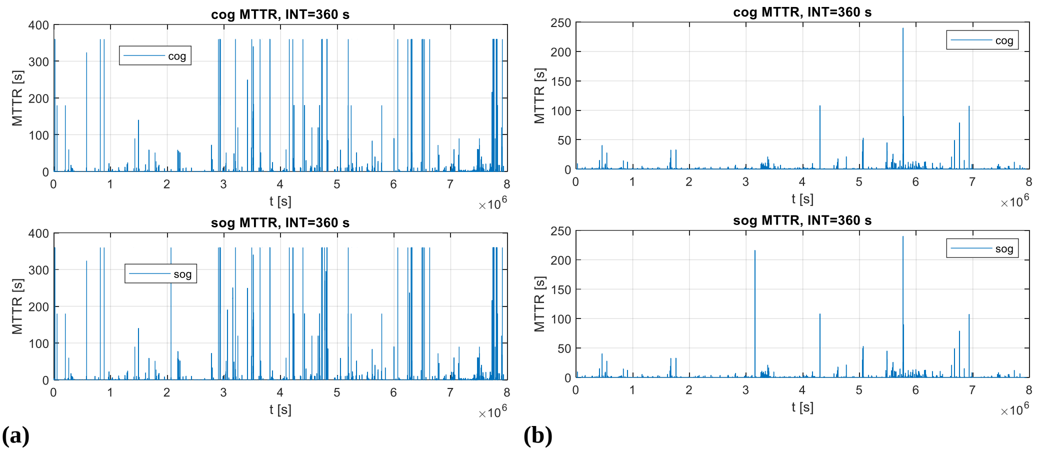


Fig. 6. Mean time to repair based on the age of dynamic data at 360 s intervals for the parameters COG and SOG, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

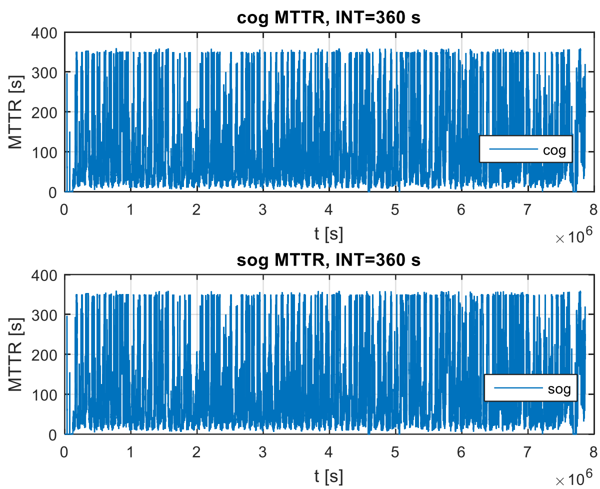


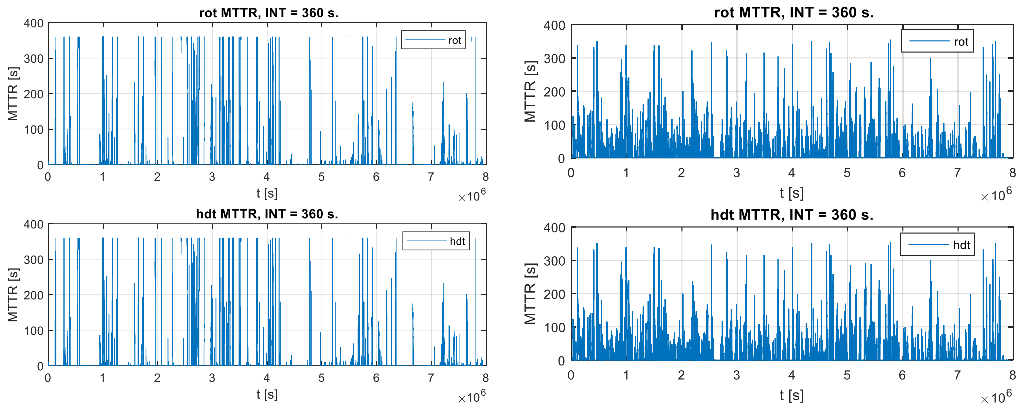
Fig. 7. Mean time to repair based on the age of dynamic data at 360 s intervals for the parameters COG and SOG, based on the dynamic data recorded by the station PLSZZ

The MTTR values determined for the COG parameter occasionally indicate an extended age of the dynamic data recorded by the PLKOL, PLSWI AIS receivers. The MTTR values for the COG parameter based on the dynamic data recorded by the ground station PLSZZ take values that are significantly higher than the dynamic data recorded by the PLKOL, PLSWI AIS receivers. The MTTR values determined for the SOG parameter based on the dynamic data recorded by the PLKOL and PLSWI receivers are the same as those for the COG parameter. The MTTR values determined for the SOG parameter based on the dynamic data recorded by the ground station PLSZZ mostly have the values TTR = 360 s. This phenomenon is common for monitoring areas with moored or anchored vessels.

The MTTR values determined for the parameters HDT and ROT had the highest values (Fig. 8 and 9).

The dynamic data age values for the parameter HDT, based on the dynamic data recorded by ground stations PLKOL and PLSWI, are similar. The different MTTR results for the parameter HDT originate from the station PLSZZ. AIS service for navigation parameters HDT and ROT are characterised by a high damage level as compared to the parameters LAT and LON. FFT was used to present the frequency of occurrence of the MTTR result in the six-minute samples. The MTTR spectrum of the parameters LAT and LON in the domain of frequency (Fig. 10 and 11) is characterised by frequent changes in MTTR.

Navigation parameters LAT and LON are generated by shipboard positioning system receivers, where their resistance to defects is affected by the positioning service availability. The MTTR spectrum of the parameter SOG is characterised by a higher amplitude of the main component 1.2 s for the dynamic data recorded by the ground station PLKOL and the amplitude 0.3 s for the dynamic data recorded by the ground station PLSWI. A higher amplitude MTTR = 80 s was observed for the dynamic data recorded by the ground station PLSZZ (Fig. 12 and 13).



(a) **(b)**

Fig. 8. Mean time to repair based on the age of dynamic data at 360 s intervals for the parameters HDT and ROT, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

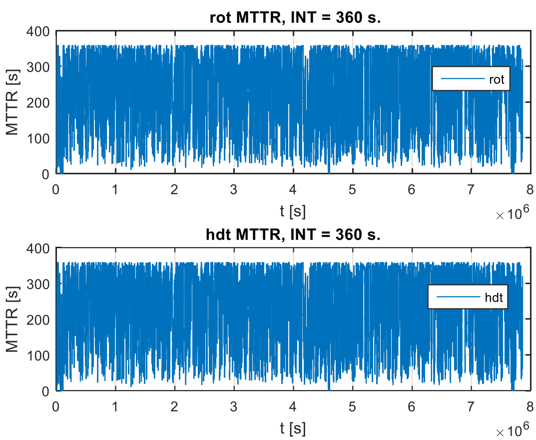
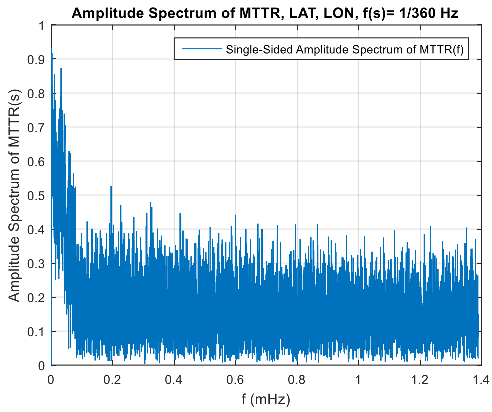
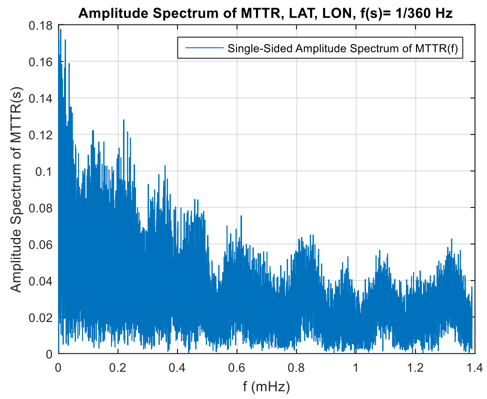


Fig. 9. Mean time to repair based on the age of dynamic data at 360 s intervals for the parameters HDT and ROT, based on the dynamic data recorded by the station PLSZZ



(a)



(b)

Fig. 10. Single-Sided amplitude spectrum of the mean time to repair for the parameters LAT and LON, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

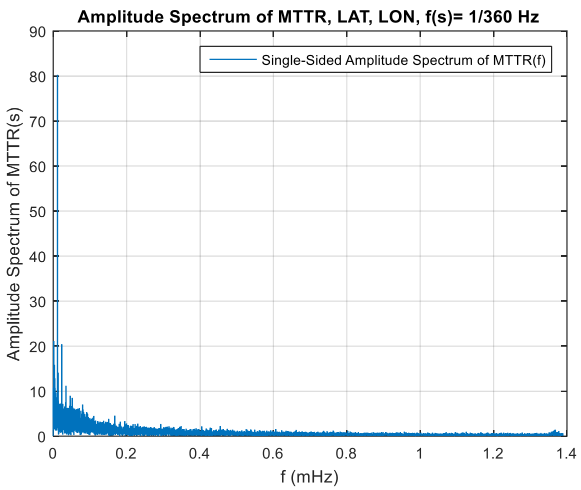
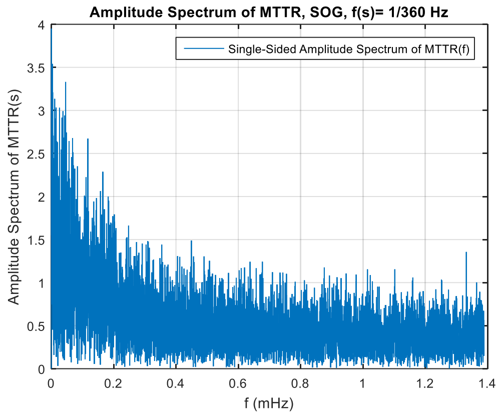


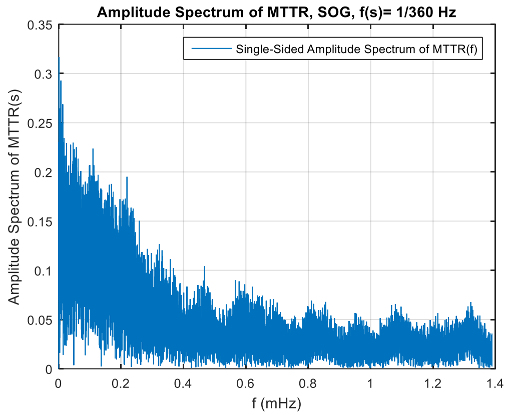
Fig. 11. Single-Sided amplitude spectrum of the mean time to repair for the parameters LAT and LON, based on the dynamic data recorded by the station PLSZZ

Interference with the transmission of a pseudo-random code in the satellite-vessel relation reduces the availability of the positioning system while increasing TRR for the above-mentioned three navigation parameters of the AIS system. The MTTR spectrum for the parameter COG is characterised by the main harmonic component similar to the parameter SOG (Fig. 14 and 15).

Errors resulting from accidental interference with the positioning service reduce the AIS service quality. Harmonic components with a maximum amplitude from 0.2 s to 80 s MTTR occur for low frequencies of 0.0001 Hz. Outliers for the main harmonic components can be filtered using a high-pass filter with a finite impulse response (FIR). The AIS service for the navigation parameters LAT, LON, and SOG is characterised by a low failure rate as compared to the navigation parameters COG, HDT, and ROT (Fig. 16 and 17).



(a)



(b)

Fig. 12. Single-Sided amplitude spectrum of the mean time to repair for the parameter SOG, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

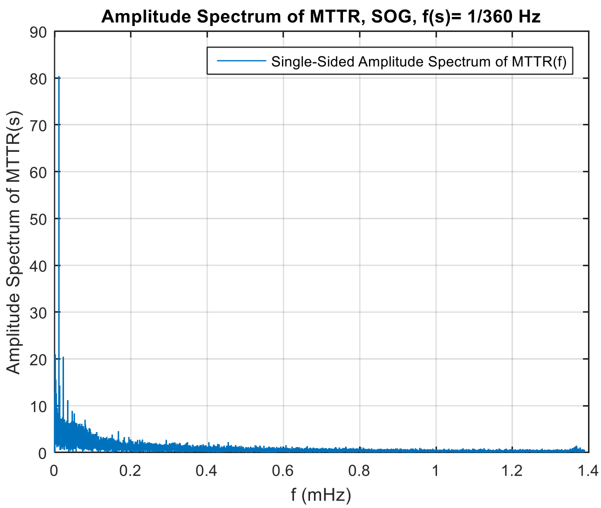


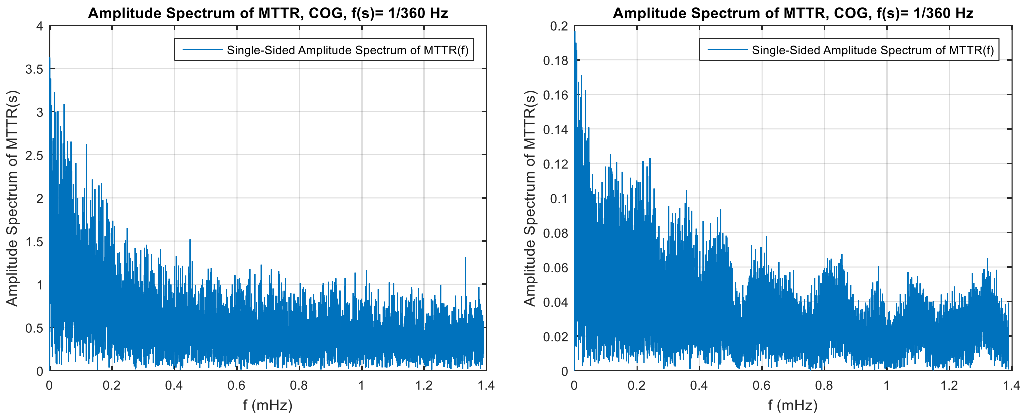
Fig. 13. Single-Sided amplitude spectrum of the mean time to repair for the parameter SOG, based on the dynamic data recorded by the station PLSZZ

The maximum MTTR spectrum amplitude takes values from 8 s for the PLKOL receiver to 23 s for the PLSZZ receiver. It was observed that at low vessel speeds and for moored vessels, the frequency of occurrence of the extended dynamic data age is considerably higher. This is particularly noticeable for the data recorded from the station PLSZZ.

The MTTR amplitude spectrums for the parameters ROT and HDT take the same form. The source of this data is usually the gyrocompass.

Based on the MTTR and MTBF determined for p navigation parameters and m data streams, the service availability was determined for each navigation parameter. Then, based on the TTR quantisation process, the system service was classified into a specified state from the set S_t.

Detailed results of the service quantisation process for *p* navigation parameters, with an indication of the total number of transitions between the particular service states, are provided in Table 3.



(a) **(b)**

Fig. 14. Single-Sided amplitude spectrum of the mean time to repair for the parameter COG, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

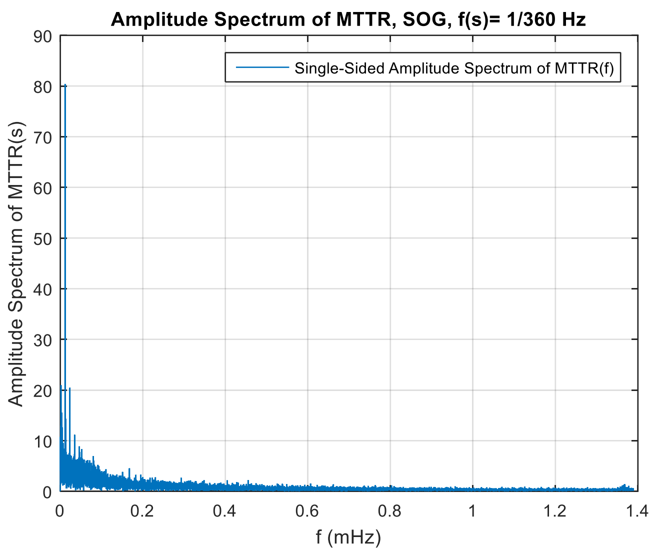
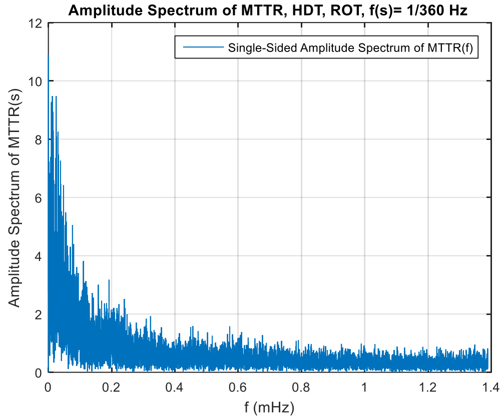


Fig. 15. Single-Sided amplitude spectrum of the mean time to repair for the parameter COG, based on the dynamic data recorded by the station PLSZZ

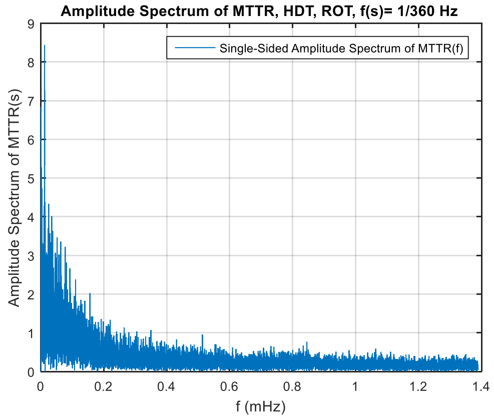
According to the location of the receiver, low AIS service availability was observed for each of the p navigation parameters contained in the position reports recorded by the station PLSZZ. Similar results of service availability for dynamic parameters, whose source of origin is the positioning system, were noted for the PLSWI and PLKOL receivers. Varying results of the AIS service availability were observed for parameters whose source of data origin is the gyrocompass. The quality of the dynamic data service is determined, among other things, by the speed of the vessels. Anchored and moored vessels generate an above-average age of dynamic data, which exceeds the transmission interval.

The presented mathematical model can be applied to monitor the operational characteristics of the AIS service at the level of individual vessels, which in real-time would determine which data streams indexed by MMSI number contain incomplete data in their content. The implementation of the model can also be carried out in Vessel Traffic Services (VTS) centers, where continuous monitoring of AIS service availability in real-time can be conducted.

Further research on the availability of the AIS service should be expanded to include additional variables in the form of positional reports from Class B devices. The studies should be extended to monitor dynamic outliers deviating from characteristic values. To achieve this, multi-stage neural networks should be constructed and deep learning methods should be applied to detect anomalies related to the availability of the AIS service.



(a)



(b)

Fig. 16. Single-Sided amplitude spectrum of the mean time to repair for the parameters HDT and ROT, based on the dynamic data recorded by the station (a) PLKOL, (b) PLSWI

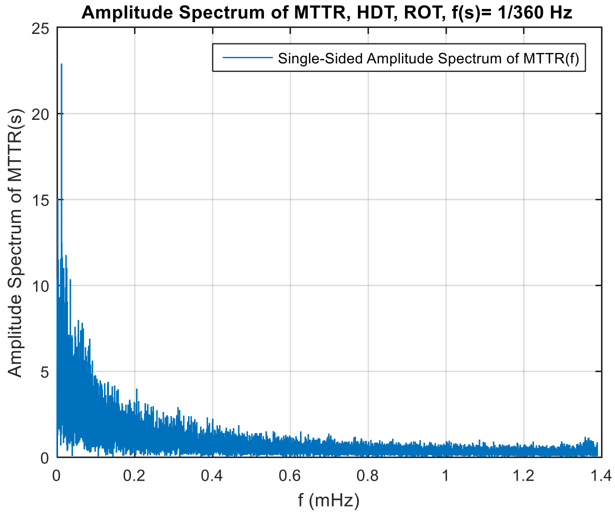


Fig. 17. Single-Sided amplitude spectrum of the mean time to repair for the parameters ROT and HDT, based on the dynamic data recorded by the station PLSZZ

Table 3. The results of classifying the system into a state from the set S_t, and the probability of being in state 1 for particular navigation parameters

navigation parameter	receiver	number of transitions from state 0 to state 0	number of transitions from state 0 to state 1	number of transitions from state 1 to state 1	number of transitions from state 1 to state 0	$P_{\Phi_{p,m}(S_t=1)}$
COG	PLKOL	71	254	21261	254	0.985
	PLSWI	20	23	21774	23	0.998
	PLSZZ	18697	800	1542	801	0.107
LAT, LON	PLKOL	271	37	21735	37	0.986
	PLSWI	20	22	21777	21	0.998
	PLSZZ	18689	804	1543	804	0.107
SOG	PLKOL	321	268	21223	268	0.973
	PLSWI	27	25	21764	24	0.997
	PLSZZ	18694	802	1542	802	0.107
HDT	PLKOL	1456	283	19818	283	0.920
	PLSWI	5255	1018	14549	1018	0.713
	PLSZZ	21589	32	186	33	0.010
ROT	PLKOL	1434	281	19844	281	0.921
	PLSWI	5250	1011	14568	1011	0.713
	PLSZZ	21604	32	33	171	0.009

6. Conclusions

This study of the AIS service availability confirms the following thesis: “Fast Fourier transform is a convenient mathematical tool presenting the amplitude spectrum of the age of dynamic data, thus determining the Time To Repair (TTR) of a selected navigation parameter coming from m data streams indexed by the MMSI number” and „The availability of the AIS service depends on the age of dynamic data p of the navigation parameter indexed with MMSI numbers assigned to AIS transmitting and receiving devices in the system operation zone”. This thesis follows from research into service availability. The feature was examined based on the dynamic data age referring to the moments when incomplete data for the six navigation parameters were received. The service availability study was preceded by an analysis of the MTTR amplitude spectrum in the domain of frequency using FFT. The study results confirmed the high service availability for the navigation parameters originating from a GPS / GNSS receiver only for receiving stations PLKOL and PLSWI. The results of research on the availability of the AIS service for the PLSZZ station contradict this thesis “ The availability of the AIS service determined on the basis of the age of dynamic data from 3 receiving stations on the Polish coast (Kolobrzeg, Swinoujscie, Szczecin) has values similar to each other and does not differ from the availability of the AIS service determined in an earlier period for other areas of the Polish coast” The results of the three-month data recording from the PLSZZ station differ significantly from the results from the PLKOL and PLSWI stations and from the research results from receiving stations from other areas of the Polish coastwhich were carried out earlier(Jaskólski, 2022). The application of FFT to examine the frequency of failures of the service specified by the MTTR moments was adopted as the main objective of the study. The aim was achieved by determining the amplitude characteristics for the six navigation parameters in the domain of frequency. The sampling frequency of 1/360 Hz was referred to the duration of recording a single sample, i.e. six minutes. Both the service failure moments and MTTR for m data streams, and for p navigation parameters, were determined from each sample. The MTTR spectral analysis shows the frequency of MTTR emergence from a sample of 21 840 six-minute samples. The method of presenting MTTR in the domain of frequency offers a better representation of the expected MTTR value than the presentation of the study results in the domain of time. Assuming that the damaged components of the AIS service structure are independent, the AIS service availability could be determined. This provides an overall view of the availability of navigation parameters contained in position reports from A-class devices. Analysing the results of the AIS service availability at the moment of system implementation and the occurrence of incomplete data for p navigation parameters and m data streams, presented in this article, is a common phenomenon.

The navigation parameters provided by vessels located within the area of operation of their own AIS device are often incomplete, which makes the vectors of the objects-vessels not very credible.

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