Operational Research of AIS AtoNs in Inland Waterways: A Case Study of a Selected Stretch on the Danube

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This study investigates the deployment and operational performance of AIS Aids to Navigation (AtoNs) on the Danube River, focusing on a selected 9-kilometer stretch in Slovakia. The research is aimed at assessing the radio visibility, energy consumption, impact on VHF Data Link (VDL) load, and positional accuracy of the deployed buoys, providing insights for future implementations on inland waterways. Radio visibility has remained stable, with a success rate of over 90% for receiving transmitted AIS messages during uninterrupted operational periods. However, high water levels have disrupted operations by sweeping buoys away, necessitating re-deployment. Energy consumption analysis has revealed that AtoN Type 1, which operates without sensors, has maintained a stable battery voltage above the critical level (12.4 V) throughout the test period, even during cloudy conditions. For AtoN Type 3, the battery has also remained stable without sensors. However, when operating in repeater mode or with sensors, the battery levels have dropped below the critical point during extended periods of reduced sunlight, leading to communication failures and necessitating external charging. The study has also evaluated the VDL load impact, finding it minimal, even when the buoys operating in repeater mode. Specifically, AtoNs without sensors has been used only 0.6% of the available VDL slots, indicating a negligible effect on the overall system. Positional accuracy has been was assessed by analysing "off-position" alerts. Initial settings have shown frequent off-position reports, especially during high water conditions. Adjusting the radius to 150 meters has significantly reduced these alerts, achieving near-perfect position retention during the final testing phase, except for occasional deviations likely due to environmental factors. While AIS AtoNs shows promise for enhancing inland waterway navigation, challenges such as anchoring stability during high water, energy management, and precise positioning require further refinement. These findings are critical for guiding the broader deployment of AIS AtoNs in inland waterways.

KEYWORDS
~ AtoNs
~ AIS
~ Inland waterways
~ Danube

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1. INTRODUCTION

Automatic Identification System (AIS) Aids to Navigation (AtoNs) is a transformative technology in the realm of inland waterway transport, offering advanced capabilities for navigational safety and operational efficiency (Balduzzi, et a., 2014). AIS AtoNs provides real-time data regarding vessel movements, which is crucial for preventing accidents and optimising traffic management (Goudossis & Katsikas, 2019). AIS AtoNs come in three primary forms: physical, virtual, and synthetic. Physical AIS AtoNs are traditional aids to navigation, such as buoys and beacons, fitted with AIS transceivers. Virtual AIS AtoNs do not have a physical presence but provide electronic navigation data to vessels. Synthetic AIS AtoNs are actual physical aids that are digitally represented in other locations, enhancing visibility on electronic navigation charts.

The Danube River, a major European waterway, has been a focal point for AIS AtoN implementation. Several studies (Handayani et al., 2013, Fournier et al., 2018, Dávid et al., 2024) have shown that AIS AtoNs on the Danube have improved vessel tracking accuracy and traffic management efficiency, resulting in reduced accidents and operational delays. This implementation demonstrates the potential of AIS AtoNs in enhancing inland waterway navigation. The primary benefit of AIS AtoNs is enhanced navigational safety. By providing real-time information about vessel positions, speeds, and courses, AIS AtoNs help prevent collisions and groundings (Minßen et al., 2024). The research conducted on the Rhine River has indicated a significant decrease in maritime accidents following the deployment of AIS AtoNs, highlighting the improved situational awareness for mariners. Operational efficiency is another critical advantage. AIS AtoNs facilitate precise vessel tracking and effective traffic management, reducing congestion and optimising navigation routes (Friedhoff et al., 2023). This efficiency leads to lower fuel consumption and reduced greenhouse gas emissions, contributing to environmental sustainability in inland shipping (Kendra et al., 2023, Galierikova & Sosedová, 2016). Furthermore, AIS AtoNs support better decision-making for waterway authorities. The data collected can be utilised for traffic analysis, incident response, and infrastructure planning, providing valuable insights that enhance the management of busy and critical segments of inland waterways. AIS AtoNs have substantial environmental benefits. By optimising navigation routes, they help reduce fuel consumption, leading to lower emissions of CO2 and other pollutants (Chen &Yang, 2024). Implementation of AIS AtoNs can lead to a 10-15% reduction in fuel usage, directly impacting the environmental footprint of inland waterway transport (Fan et al., 2023). Economically, the deployment of AIS AtoNs results in cost savings for the shipping industry. Lower fuel consumption and shorter travel times reduce operational costs (Mi et al., 2023). Additionally, by preventing accidents and minimising emergency responses, AIS AtoNs help decrease the financial burden associated with maritime incidents (Maternova & Materna, 2023).

Despite their benefits, deploying AIS AtoNs in inland waterways presents several challenges. One major challenge is the integration with existing navigation systems and the standardisation of AIS AtoN technologies. Variations in regulatory frameworks and technical standards across different countries can impede the seamless operation of AIS AtoNs. Maintenance and reliability are also critical issues. AIS AtoNs must operate reliably in various environmental conditions, including extreme weather and heavy traffic. Ensuring continuous operation requires robust maintenance strategies and reliable hardware, which can be costly and technically demanding. The high initial investment required for implementing AIS AtoNs is another significant challenge. The costs associated with the installation, operation, and maintenance of these systems can be a barrier, particularly for regions with limited financial resources. Ensuring the security of AIS AtoNs is vital for their reliable operation and the safety of inland waterway transport. Cybersecurity threats, such as data spoofing, jamming, and hacking, pose significant risks to AIS AtoNs. These threats can lead to incorrect navigational information, potentially causing severe accidents (Bošnjak et al., 2012).

Several measures are essential for securing AIS AtoNs:

- Encryption and Authentication: Implementing robust encryption and authentication protocols to protect data integrity and prevent unauthorized access.
- Regular Updates and Patching: Keeping system software up-to-date with the latest security patches to mitigate vulnerabilities.
- Monitoring and Incident Response: Establishing continuous monitoring systems to detect and respond to security breaches promptly.
- Training and Awareness: Providing training for operators and stakeholders on cybersecurity best practices and protocols.

International collaboration and information sharing among countries and organisations can enhance AIS AtoN security. By sharing threat intelligence and security strategies, stakeholders can develop more comprehensive and effective security measures. To address these challenges, ongoing research and international collaboration are essential. Standardising AIS AtoN technologies and harmonising regulatory frameworks will facilitate broader adoption. Advances in technology, such as developing more durable and cost-effective AIS equipment, can help overcome financial and technical barriers to implementation. Currently, inland navigation lacks a standardised framework, leading to inconsistencies in the application of AtoNs, which is crucial for ensuring safety. The non-standard AtoNs in use can cause confusion and heighten navigation risks. A study focused on Kenyir Lake in Malaysia highlights the need for an appraisal of the existing practices to enhance the safety and efficiency of navigation. This study aims at developing a standardised, cost-effective AtoNs design, aligned with IALA guidelines, addressing both operational and economic concerns as the lake sees increasing usage (Hasbullah & Osnin, 2020). Freight Travel Demand Models (TDMs) often lack sufficient detail for evaluating multi-modal infrastructure, particularly for non-truck modes. However, the expanded availability of AIS data offers an opportunity to enhance the representation of maritime modes within freight TDMs. By applying network mapping heuristics to AIS data, vessel trips can be accurately identified and used for various analytical purposes, such as generating origin–destination matrices and calculating time impedances (Asborno et al., 2022). The AIS is crucial for maritime surveillance and shipping. Recent advancements in AI enable the extraction of valuable insights from AIS Big Data. However, deploying multiple AI models for complex maritime tasks remains challenging. A study by Li et al. (2024) develops an AIS-based deep learning model that addresses forecasting, classification, anomaly detection, and imputation. AIS data, along with data from navigational buoys, can also be used to establish liability in the event of an accident. This issue is explored in a study by Liu et al. (2022), where they develop a probabilistic analytical method to assess the risk of ship-to-buoy collisions in coastal areas, a method that is equally applicable to inland waterways. Kelly (2022) focused on detecting AIS transponder interference developed a technique to identify vessels switching from normal to low transmit power mode by analysing the Received Signal Strength Indicator (RSSI) of AIS messages. Using data from the Irish National AIS, the research revealed that a specific drop in RSSI, approximately 10 dBm, could be detected at various distances from the receiving base station. This method provides a novel approach to identifying potentially nefarious activities by monitoring changes in AIS signal strength. Berbić et al. (2023), in a study focused on the AIS, highlighted its role in enhancing maritime safety by providing detailed information on ships' identification, position, speed, and course. It explored the use of machine learning techniques to process AIS data for various applications, such as extracting vessel trajectories, assessing collision risk, detecting maritime anomalies, and analysing ship emissions. The research emphasised the significant impact of these techniques in quickly processing large data sets, thereby increasing the safety and reliability of maritime transport. A study by Ray et al. (2019) on the AIS focused on monitoring, analysing, and visualising maritime traffic using AIS data alongside additional contextual maritime data. The research compiled a comprehensive dataset that includes navigation, vessel-oriented, geographic, and environmental data, covering a six-month period and various maritime regions. This dataset, designed for easy integration with relational databases like PostgreSQL and its geospatial extension PostGIS, aims at enhancing the understanding of maritime activities and their environmental impacts. To optimise the placement of AtoNs, performance measures that quantify the effectiveness of AtoN placement are essential. The ideal placement ensures that navigators can clearly recognise the information provided, which depends on factors like light contrast, weather conditions, and navigator position. These performance measures, grounded in human factor values recommended by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), are evaluated by using the AtoN Simulator developed by KIOST/KRISO, with simulations conducted at Busan port, Korea (Fang et al., 2015).

This scientific paper focuses on the pilot operation of AIS AtoN components on inland waterways, using the Danube River as a case study. The aim is to explore the implementation, benefits, challenges, and security issues associated with AIS AtoNs, providing a comprehensive overview that can inform future deployments.

2. METHODOLOGY

This study focuses on the deployment of buoys in the selected Slovak section of the Danube River, starting at rkm 1871 and ending at rkm 1862 (Figure 1). A total of eight buoys utilising AIS (Sealite) technology were installed in accordance with an approved delineation plan, following the acquisition of necessary permits.

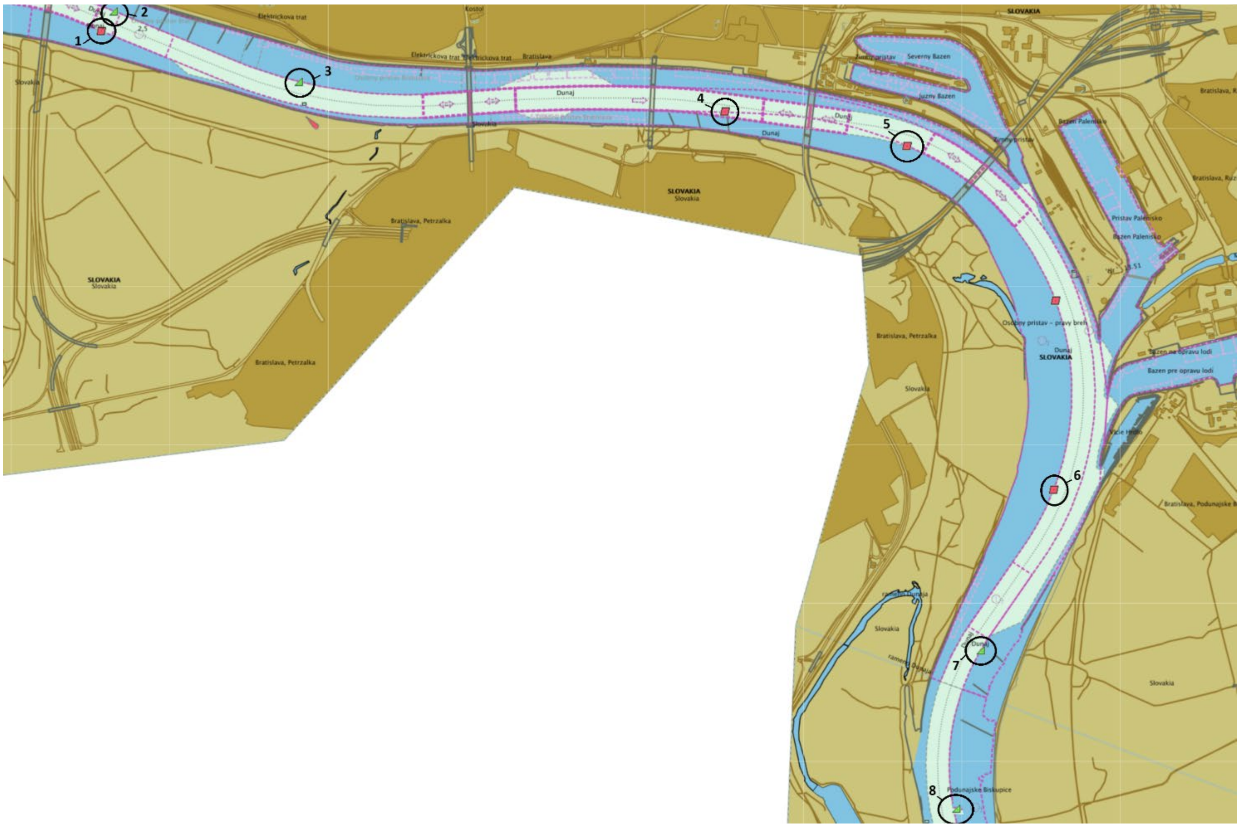

Figure 1. Deployment of Buoys in the Selected Section of the Danube River (Source: d4d-portal.info, authors).

Several types of AIS AtoN buoys were tested. AtoN Type 1 buoys are capable of transmitting AIS messages only and do not support reception. AtoN Type 3 buoys were tested in multiple configurations: without sensors, with temperature and depth sensors, and in both repeating and non-repeating modes (Table 1).

	Colour	rkm	GPS N	GPS E	MMSI	AIS type	AIS additional equipment/functions
1	red	1871.04	48.141289768	17.079005760	267100001	3	sensors for measuring depth and temperature
2	green	1871.02	48.142210057	17.079863660	267100002	1	
3	green	1870.00	48.138942863	17.092671367	267100003	3	
4	red	1867.78	48.137562192	17.122278374	267100004	1	
5	red	1866.80	48.135958330	17.134859261	267100005	3	
6	red	1864.50	48.120042175	17.145055141	267100006	3	repeat mode
7	green	1863.75	48.112589019	17.140045042	267100007	3	sensors for measuring depth and temperature
8	green	1862.62	48.102954725	17.139187164	267100008	3	

Table 1. Types of AIS AtoN Buoys and Their Configurations (Source: Authors).

In the first phase, the crew practiced buoy handling in both a port basin and on the open flow of the Danube River. One buoy was temporarily operated in the port basin. In the second phase, buoys 1 - 4 were deployed, followed by the deployment of buoys 5 - 8 in the third phase.

After the deployment of buoys between rkm 1862.6 and rkm 1871.0, the software was activated to monitor the buoy positions and record AIS system communication, as well as data transmission from sensor-equipped buoys. Regular maintenance and reconnection of the AtoN AIS collector to the SlovRIS AIS system after automated server disconnection were part of the process. The software was adjusted to load and display current or most recent AtoN data details on the map, including the visualisation of AtoN icons.

2.1. Operation and Testing

During the operation on the reference section, an extraordinary increase in water level caused the buoys to drift from their original positions, resulting in damage to some AIS modules. The buoys exhibited varying behaviour under different flow speeds, ranging from 1 to 3 m/s in the deployment area. Buoys near the Lafranconi Bridge (Figure 2) showed tilting, while those under the harbour bridge remained stable (Figure 3).

Figure 2. Green Buoy at rkm 1871.0 (Source: Authors).

Figure 3. Green Buoy at rkm 1863.7 (Source: Authors).

The tilting of the buoys did not affect the reliability of AIS communication. The buoys are typically anchored using a mooring chain. The weight and length of the chain were designed in accordance with the recommendations for the specific type of buoy.

2.2. Radio Visibility Range

Visibility (Vr) is statistically evaluated based on the number of AIS messages received from the AtoNs by base stations, compared to the expected number of transmitted messages No. 21 (Figure 4).

AtoN Status - AIS Data

Time	AtoN	MMSI			Hectometer	Type of Lamp	GPS N	GPS E
07.12.2021 13:54	GREEN BUOY S...	267100008			18626	SL410	48.10245700	17.13925800
07.12.2021 13:54	GREEN BUOY S...	267100008			18626	SL410	48.10245700	17.13925800
07.12.2021 13:54	GREEN BUOY S...	267100008			18626		48.10245700	17.13925800
07.12.2021 13:54	GREEN BUOY S...	267100002			18710	SL410	48.13899300	17.09300200
07.12.2021 13:54	GREEN BUOY S...	267100002			18710	SL410	48.13899300	17.09300200
07.12.2021 13:54	RED BUOY SK06	267100006			18645		48.12122800	17.14570200
07.12.2021 13:54	RED BUOY SK04	267100004			18678	SL410	48.13762500	17.12165300
07.12.2021 13:54	RED BUOY SK04	267100004			18678	SL410	48.13762500	17.12165300
07.12.2021 13:51	GREEN BUOY S...	267100008			18626	SL410	48.10245800	17.13926000
07.12.2021 13:51	GREEN BUOY S...	267100008			18626	SL410	48.10245800	17.13926000

Figure 4. AIS data message No. 21 (Source: Authors).

The expected number of transmitted messages is one message every three minutes.

$$Vr = \frac{m_a}{m_s} \cdot 100, \quad (1)$$

where m_a denotes expected messages and m_s transmitted messages.

2.3. Energy Consumption

Battery voltage is transmitted by the AtoN within the AIS message. Energy consumption is evaluated by monitoring the frequency of battery voltage levels depending on the following parameters:

- Type of AtoN,
- Sensor equipment (temperature and water depth measurement),
- Repeater mode setting,
- Transmission power (2 W, 12.5 W),
- Transmission interval settings,
- Settings for different types of transmitted messages (number of slots),
- Use of a light (not evaluated, as buoy lighting is not used in the selected section according to the delineation plan),
- Reference values for low battery level are ≤ 11.5 V and for depleted battery level they are ≤ 10.5 V,
- The AtoN sets flags in the message (Flat_Battery, Low_Battery) upon reaching these voltage levels.

2.4. Impact on VDL (VHF Data Link) Load

VDL load is determined by the ratio of currently occupied slots in the channel divided by the number of available slots within Time Division Multiple Access (TDMA).

$$VDL = \frac{S_o}{S_a} \cdot 100 \quad (2)$$

where S_o denotes occupied slot and S_a is available slot.

2.5. Off-position (Evaluation of Deviation from Defined Position)

The AIS AtoN can be configured to set a designated position and a radius to evaluate the buoy's position as on-position or off-position. If the buoy moves beyond the designated radius from its set position, it is flagged as "off-position." By tracking the changes in the AtoN's position, the density of deviations from the set position is evaluated.

3. RESULTS OF THE EXPERIMENTS

3.1. Radio Visibility Range

After placing the AtoNs at designated locations, visibility was verified by receiving AIS messages from each device. The selected section is sufficiently covered by the AIS signal from the Bratislava base station. All AtoN devices were visible upon placement. The long-term stability of the radio AIS signal for inland AIS AtoNs is evaluated based on the ratio of transmitted to actually received AIS messages. Time intervals with uninterrupted operation are selected. From July 14th to September 23rd 2021, operations were interrupted due to the buoys being swept away by high water levels.

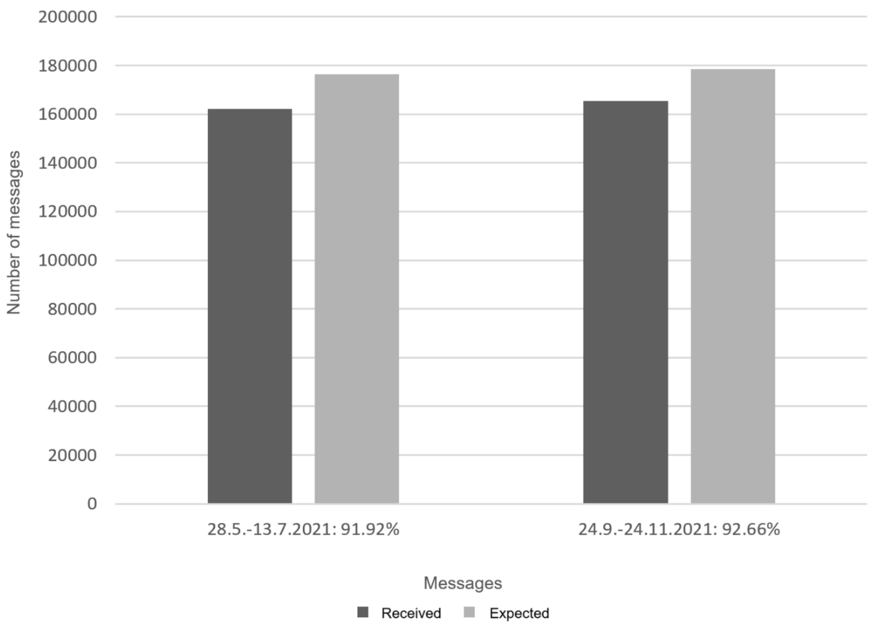

Figure 5. Ratio of received to expected messages (Source: Authors).

Figure 5 shows the evaluation of radio visibility and the success rate of receiving transmitted AIS messages from the AtoNs. During the selected operational interval, the success rate was above 90%.

3.1.1. Energy Consumption

Evaluation of energy-independent operation of AtoNs during test operation.

3.1.2. Battery Voltage for Type 1 AIS AtoNs

Set parameters:

- FATDMA access scheme. FATDMA is a manually managed TDMA access scheme where AIS devices are pre-configured to use specific TDMA slots for all transmissions. FATDMA is used only for AIS base stations and AIS AtoN stations.
- Without sensors.
- Transmission power: 12.5 W.
- Broadcast interval: 3 minutes.
- Sent messages: No. 21, No. 6, 3 slots.

Figure 6 shows the number of individual measurements for the corresponding battery voltage value for AtoN Type 1 for the entire period. The battery voltage level has not dropped below the limit level.

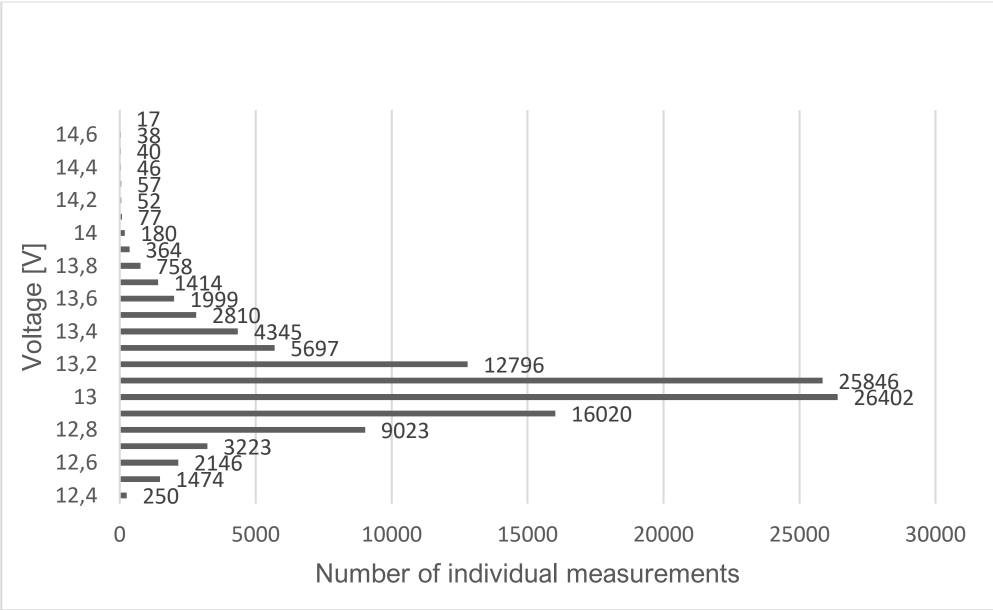

Figure 6. Number of individual measurements to the corresponding battery voltage value for AtoN Type 1 for the testing period from July 14th to September 23rd 2021 (Source: Authors).

Based on the recorded data, the battery level consistently remained above 12.4 V throughout the given time interval. The measured voltages and corresponding weather conditions are shown in Figure 7.

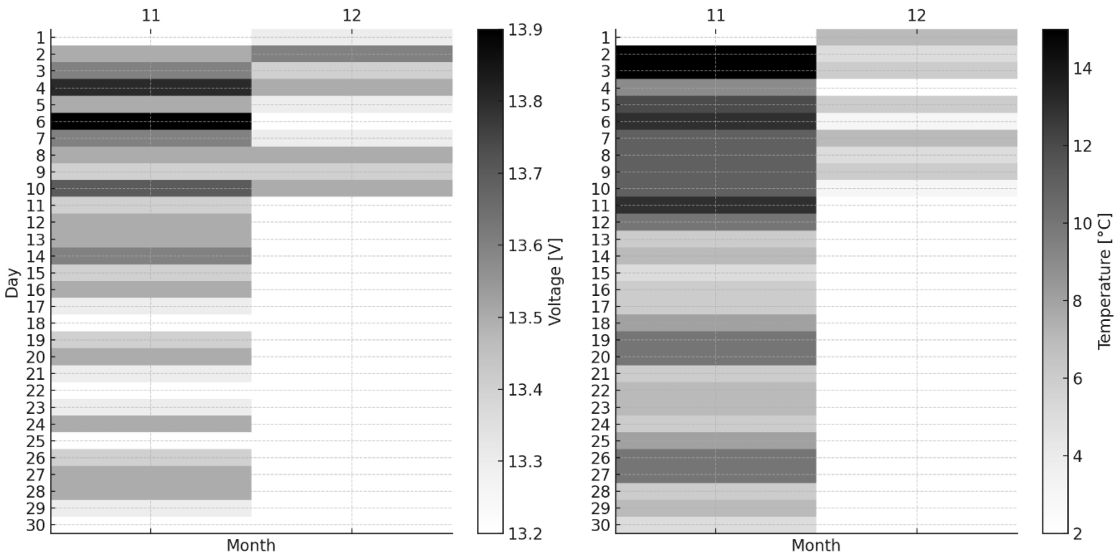

Figure 7. Voltage values for AtoN Type 1 and corresponding weather conditions for individual days (Source: Authors).

3.1.3. Battery Voltage for Type 3 AIS AtoNs – without sensors

Set parameters:

- RATDMA access scheme. RATDMA is a simple TDMA access scheme available for certain types of data transmission and AIS device types.
- Without sensors,
- Transmission power: 12.5 W,
- Broadcast interval: 3 minutes,
- Sent messages: No. 21, No. 6, 3 slots.

Figure 9 shows the number of individual measurements for the corresponding battery voltage value for AtoN Type 3, without sensors, without AIS forwarding for the entire period. The battery voltage level has not dropped below the limit level.

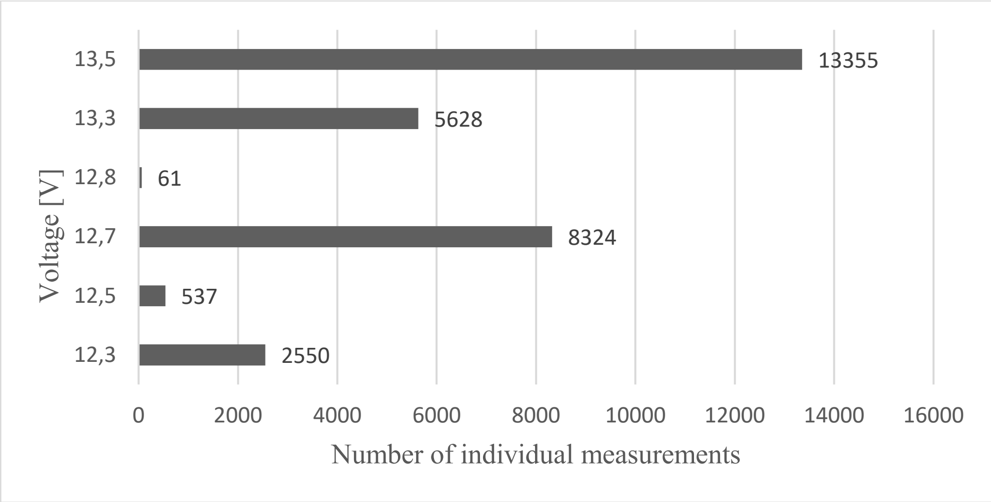

Figure 8. Number of individual measurements to the corresponding battery voltage value for AtoN Type 3 for the entire period (Source: Authors).

So far, type 3 AtoNs without sensors show reliable operation even on cloudy days. The batteries are recharged during sunny days, where the increase in battery voltage can be seen according to the Figure 9.

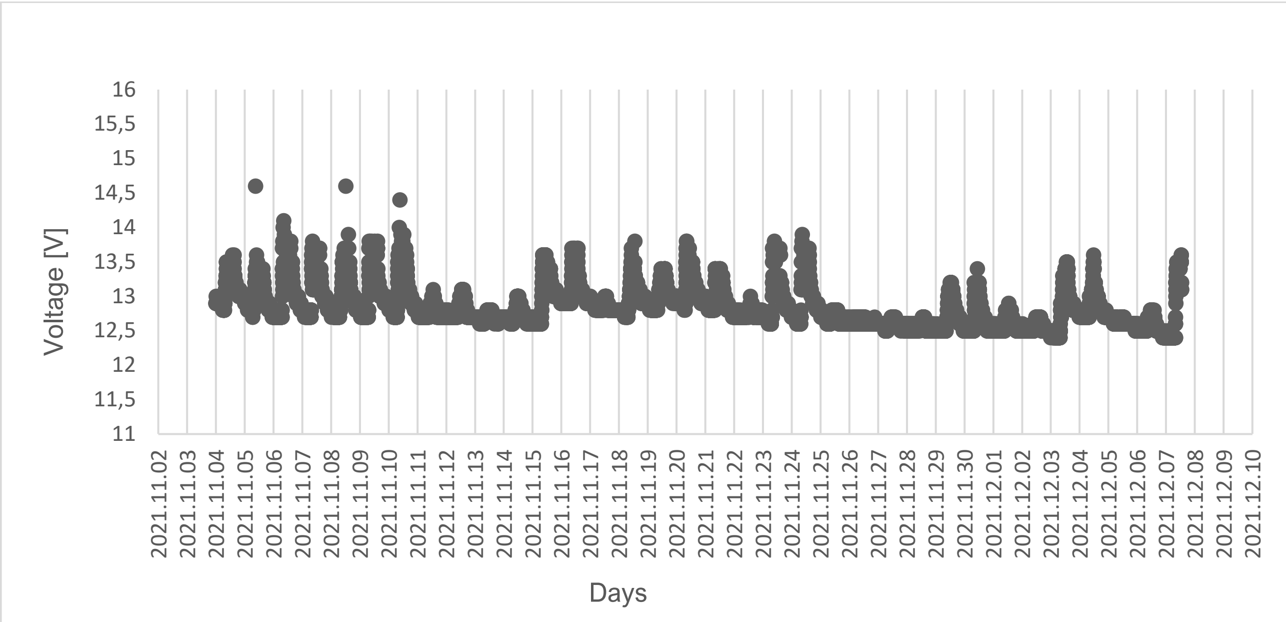

Figure 9. Voltage value for AtoN Type 3 for individual days (Source: Authors).

3.1.4. Battery Voltage for Type 3 AIS AtoNs – without sensors, repeater mode

Set parameters:

- AtoN Type 3.
- Repeater mode from 25.11.2021 for messages no. 21, no. 8 and no. 6 without distance limitation with a 30-second message tracking interval for forwarding.
- Without sensors.
- Transmission power: 2 W.
- Broadcast interval: 3 minutes.

Figure 10 shows the number of individual measurements for the corresponding battery voltage value for AtoN Type 3, without sensors, in AIS forwarding mode. The battery voltage level has dropped below the limit level. AtoN stops communicating. It is necessary to charge the battery using a charger.

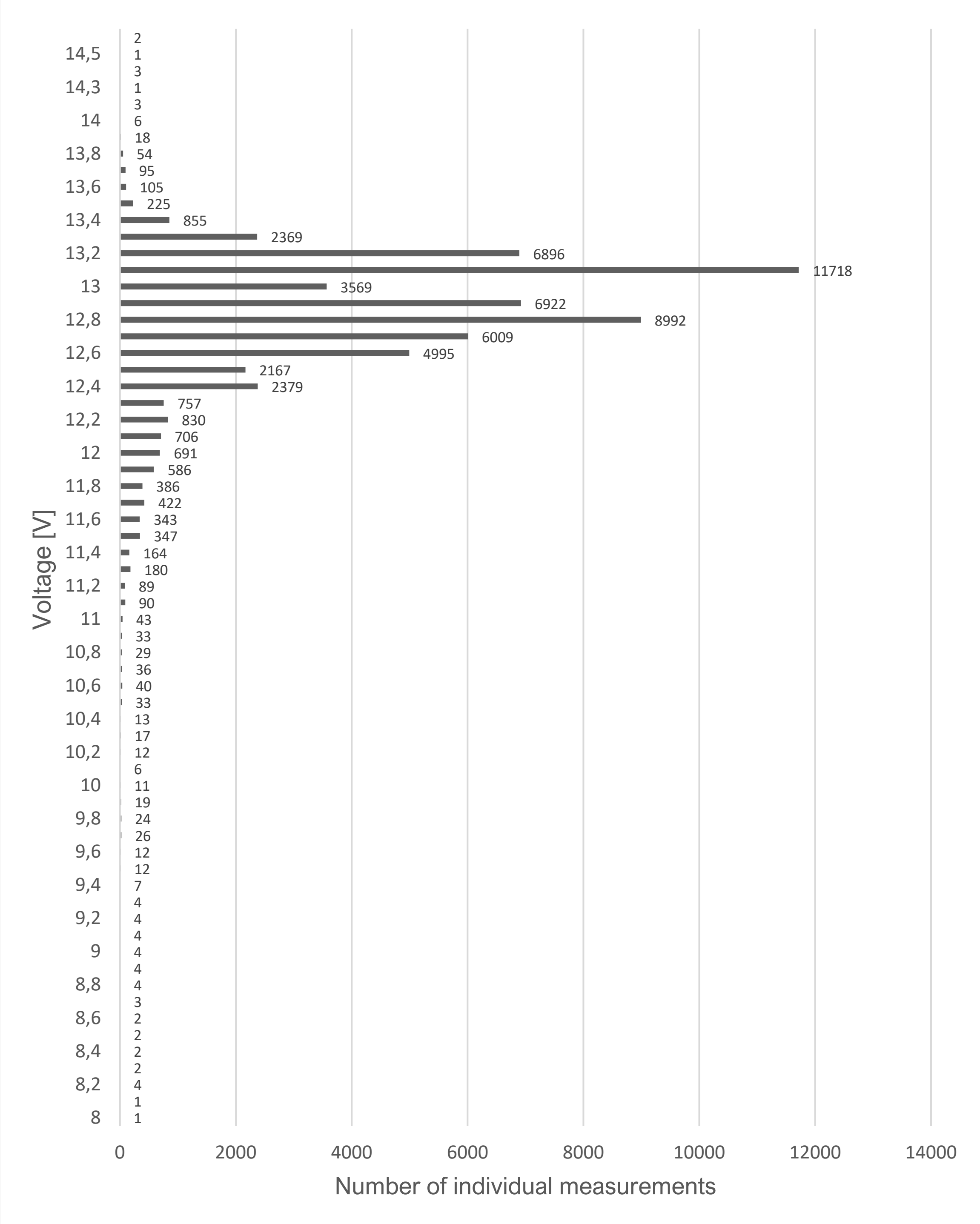

Figure 10. Number of individual measurements to the corresponding battery voltage value for AtoN Type 3 for the entire period (Source: Authors).

In Figure 11 the data indicates that around November 26th 2021 there was an increase in cloud cover in the Bratislava area. This led to a decrease in the energy production of the solar panels, resulting in insufficient power to simultaneously charge the batteries and supply the AtoN. Consequently, the battery voltage began to drop rapidly. On December 6th 2021 the battery reached a critical level of 10 V, leading to the AtoN limiting the transmission of its message No. 6. On December 7th and 8th 2021, there was a brief recovery, and several instances of message No. 6 were sent. We can conclude that AtoN is capable of communication even under these battery conditions. In winter, it is necessary to recharge the AtoN with an external charger and to disable the repeater mode.

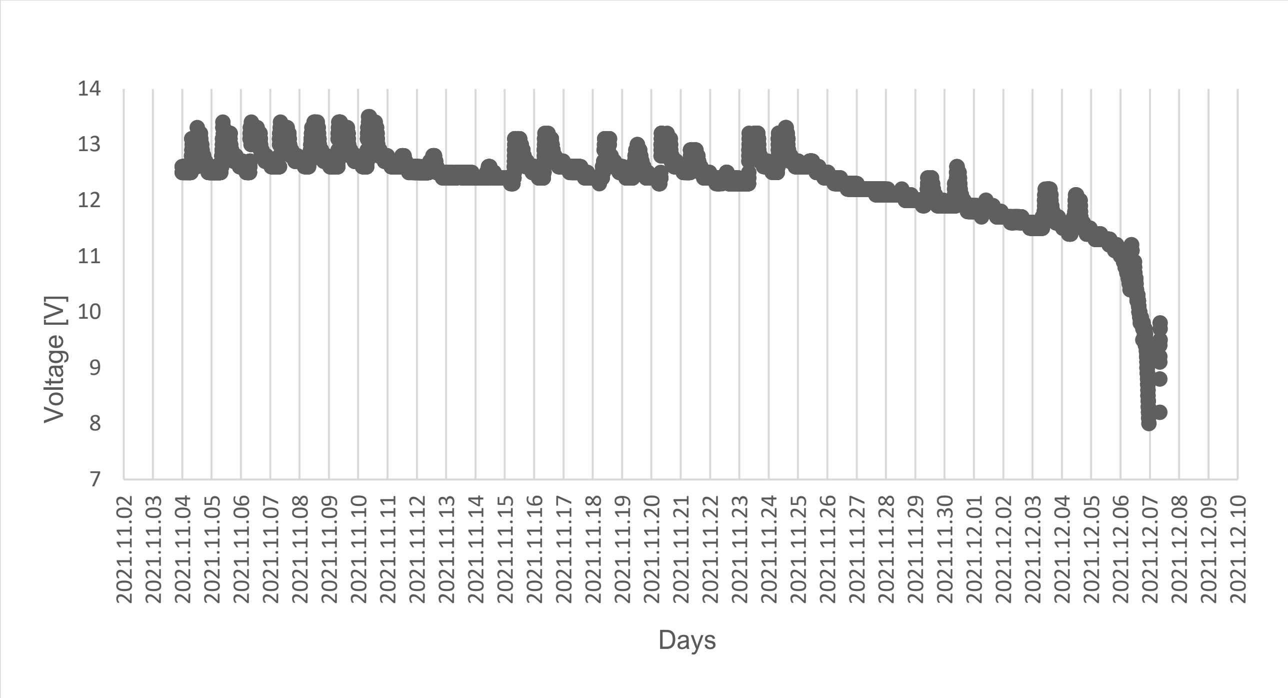

Figure 11. Voltage value for AtoN Type 3 for individual days – repeater mode (Source: Authors).

3.1.5. Battery Voltage for Type 3 AIS AtoNs – with sensors

Set parameters:

- AtoN Type 3.
- Sensors: depth measurements, water temperature measurements.
- Transmission power: 12,5 W.
- Broadcast interval: 3 minutes.
- Sent messages: No. 21, No. 6, No. 8, 3 slots.

Figure 12 shows the number of individual measurements for the corresponding battery voltage value for AtoN Type 3, with sensors, in AIS forwarding mode. The battery voltage level has dropped below the limit level.

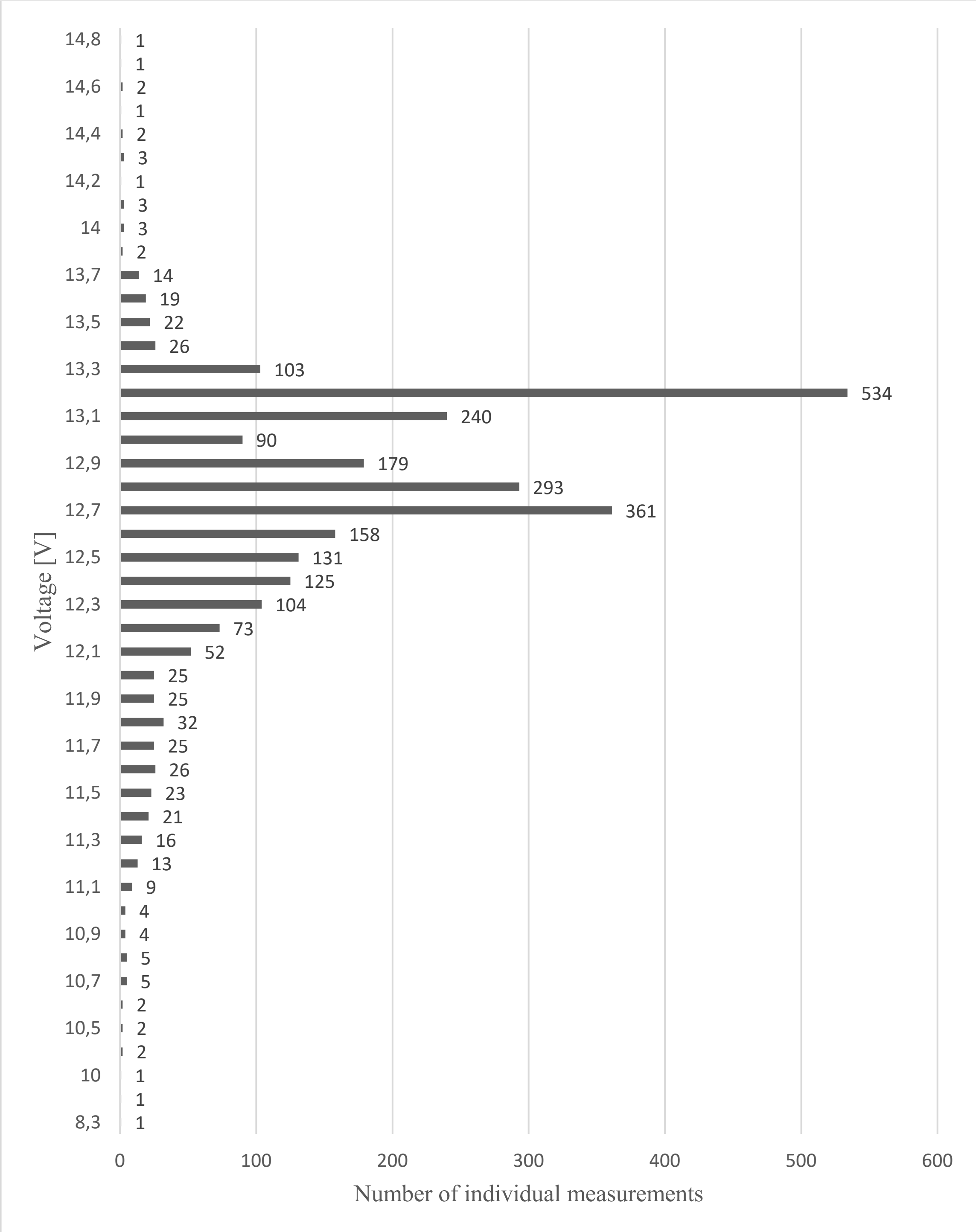

Figure 12. Number of individual measurements for the corresponding battery voltage value for AtoN Type 3 - with sensors for the entire period (Source: Authors).

From the data presented in Figure 13, it can be determined that around November 11th 2021, there was an increase in cloud cover in the Bratislava area. As a result, the solar panels were unable to produce sufficient energy to maintain battery charging, leading to a rapid decline in battery voltage. The battery reached a critical level of 10 V on November 20th 2021, at which point the AtoN system shut down. The AtoNs were subsequently retrieved for recharging using an external charger. To ensure sufficient energy, the transmission frequency of message No. 8, which reports temperature and water depth measurements, was reduced to once per hour, and the transmission power was lowered to 1 W.

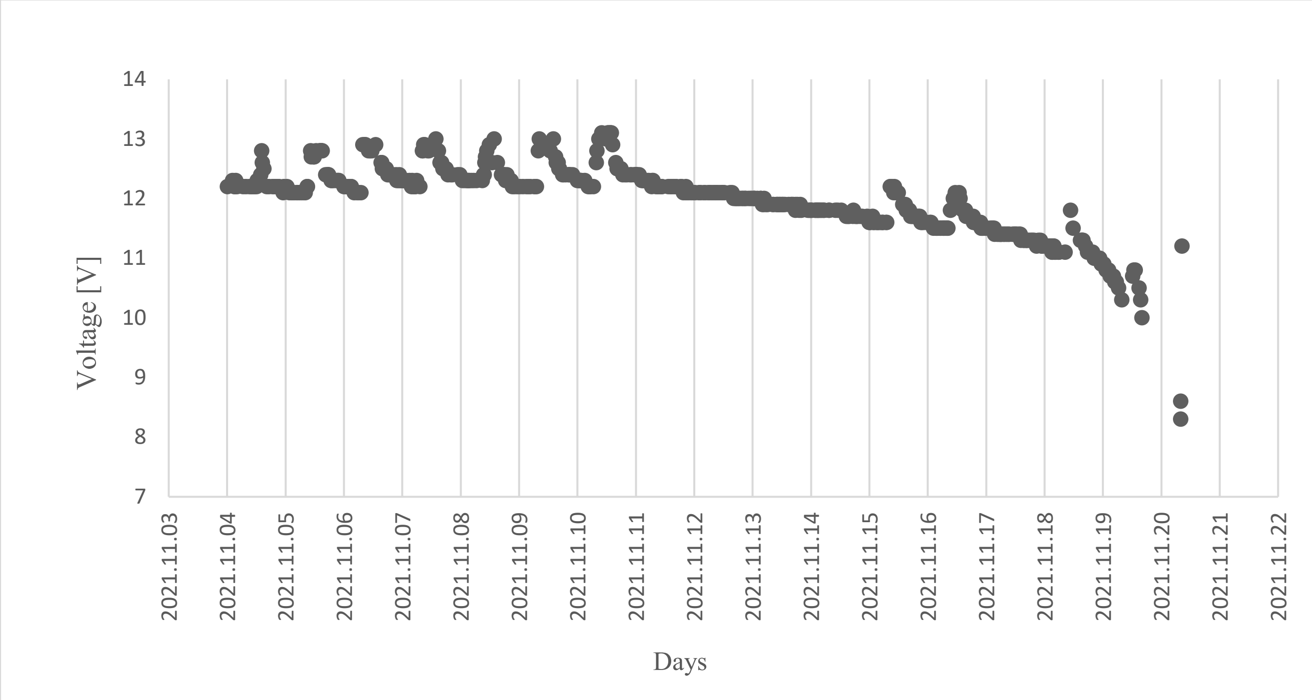

Figure 13. Voltage value for AtoN Type 3 – with sensors for individual days. (Source: Authors).

3.2. Impact on VDL Load

The AIS system uses two frequency channels (A and B) and employs Time Division Multiple Access (TDMA) technology for communication. According to the standard, each minute is divided into 2,250 time slots. Depending on the type of AIS message, the size of the message can occupy one or more slots.

The AtoN AIS module operates in three-minute intervals, with the first to third minutes dedicated to channel A, and the fourth to sixth minutes dedicated to channel B.

The slot allocation for AIS messages transmitted by AtoN is as follows:

- Message No. 21: 1 slot.
- Message No. 6 DAC990 FI22: 2 slots.
- Message No. 8 DAC1 FI31: 2 slots.

An AtoN without sensors utilises 3 slots over a 3-minute period, which corresponds to 3 out of 6,750 slots. An AtoN equipped with sensors uses 5 slots, or 5 out of 6,750 slots. In repeater mode, the AtoN doubles the number of slots used for each relayed message from other AtoNs. The AtoN only relays messages from other AtoNs, not from vessels or other AIS transponders.

The maximum VDL load without repetition, for a scenario involving 8 AtoNs using 5 slots each per transmission interval, would be 40 out of 6,750 slots, or approximately 0.6%. The impact on VDL load is therefore minimal.

3.3. Off-position

The objective is to determine the appropriate distance radius for each buoy position to avoid unnecessary "off-position" alerts. The initial radius setting of 999 meters was implemented based on the request of the waterway manager. Control measurements were conducted at selected time intervals (as shown in Table 2) under various navigational conditions.

The higher number of off-position occurrences with a 999-meter radius may be due to the increased sensitivity to minor movements. With a wider radius threshold, slight displacements caused by currents or buoy drift, which are not significant for narrower thresholds, can accumulate and be recorded as off-position events. Thus, a smaller radius tends to filter out minor movements, providing a more stable on-position count.

27.5.2021 – 28.5. 2021			13.7.2021 – 13. 8. 2021 (High water)		
MMSI	On-position	Off-position	MMSI	On-position	Off-position
267100001	235	18	267100001	2704	9
267100002	380	0	267100002	2103	1
267100003	447	0	267100003	2684	86
267100004	471	0	267100004	2871	21
267100005	122	8	267100005	2520	16
267100006	272	1	267100006	7686	7
267100007	265	1	267100007	2681	2198
267100008	275	2	267100008	2926	4072

Table 2. Frequency of off position in selected time intervals under different navigation conditions (Source: Authors).

The Figure 14 shows the ratio of buoys in position and out of position during high water.

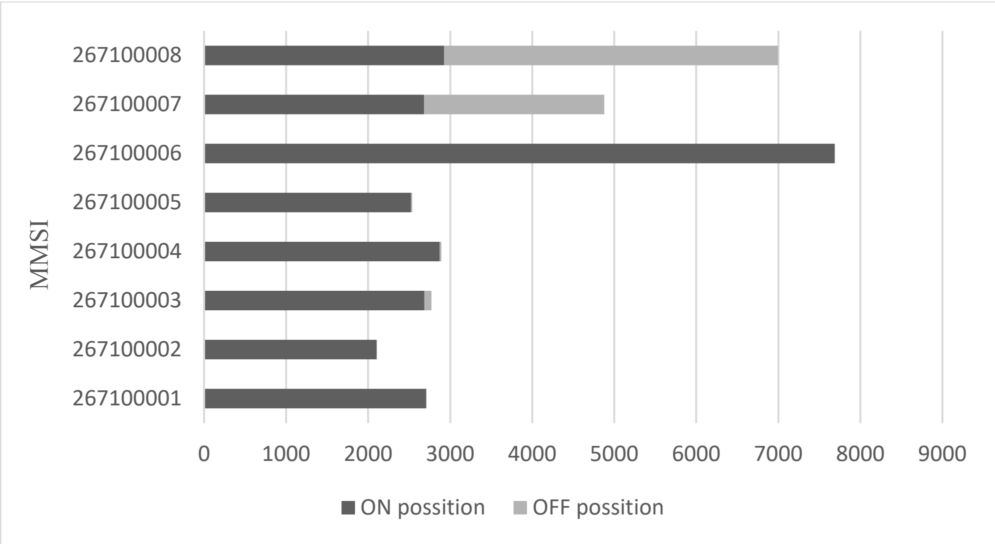

Figure 14. Ratio of buoy in position / out of position during high water (Source: Authors).

During the mentioned period during the “High water" most of the AtoNs were out of position, subsequently they were damaged, as a result of which they stopped transmitting messages altogether.

In the final phase of testing (Table 3) on the reference section, the radius was adjusted to 150 meters. The potential movement of the buoy is influenced by its deployment location, including factors such as current strength and substrate stability.

MMSI	On-position	Off-position
267100001	20534	0
267100002	17055	0
267100004	19198	0
267100006	18665	15
267100007	18374	0
267100008	17899	0

Table 3. Frequency of off position in selected time interval (24. 9. 2021 – 5. 11. 2021) (Source: Authors).

This time period can be considered ideal, as none of the AtoNs were reported outside their designated positions. However, for AtoN with MMSI 267100006, 15 messages were received indicating that the AtoN was off-position. This could have been caused by debris or similar factors. Since this situation did not recur, it can be assessed as a temporary deviation from the assigned position, followed by a return to the correct location.

This wider radius allowed for greater tolerance in buoy movement, particularly in conditions of high water and strong currents. As seen in Table 2, even with this wide radius, many AtoNs still registered as off-position during the high-water period, indicating significant displacement due to adverse environmental conditions. This suggests that even a large radius was insufficient to accommodate the extreme conditions, leading to a higher number of off-position occurrences. In contrast, the final phase of testing used a much smaller radius of 150 meters (Table 3), a more stringent threshold designed to detect smaller deviations. During this phase, conditions were more stable, with fewer environmental factors, like high water, affecting the buoys' positions. As a result, fewer off-position alerts were triggered, as the AtoNs were generally able to stay within this smaller boundary under normal conditions. This smaller radius provides more accurate monitoring of buoy positions in stable conditions, but might require adjustment in extreme situations like high water. To set the appropriate radius parameter, it is necessary to consider both the environmental conditions and the specific requirements of the waterway. In extreme conditions, a larger radius may be appropriate to account for greater movement, while in calm or normal conditions, a smaller radius can ensure more precise monitoring.

4. DISCUSSION

During the experimental investigation of energy consumption, we compared the energy requirements between AIS AtoN Type 1 and Type 3. As expected, AtoN Type 1 proved to be the least energy-intensive. This type of AtoN only supports the transmission of AIS messages and does not allow for message reception. It operates solely in FATDMA (Fixed Access Time Division Multiple Access) mode, meaning it does not listen to other AIS transmissions, and it is not equipped with sensors. During the testing phase, the minimum battery voltage recorded was 12.5 V, observed during significantly cloudy and cold weather conditions.

For AtoN Type 3 without sensors and without the repetition mode, the battery voltage showed a similar pattern to that of AtoN Type 1, with a minimum recorded voltage of 12.3 V. Active monitoring of surrounding AIS traffic occurs only when operating in RATDMA (Random Access Time Division Multiple Access) mode. In this mode, after activation, the AtoN monitors the radio frequency load and selects an appropriate time to transmit data, at which point it only sends data.

The AtoN Type 3 units equipped with sensors, specifically AtoNs MMSI 267100001 and 267100007, are fitted with temperature and water depth sensors. Their operation remained stable during the summer months. However, as weather conditions deteriorated, battery voltage began to drop on November 11th 2021, leading to the complete depletion of the batteries by November 25th, 2021. Consequently, both AtoNs were withdrawn from service. After recharging, the AtoNs were redeployed to their original positions.

For the AtoN Type 3 without sensors in repeater mode, AtoN MMSI 267100006 was configured on November 25th 2021, to repeat AIS messages specifically from surrounding AtoNs, including messages No. 21, 6, and 8, within its radio range. Messages from vessels or other types of AIS transponders were not repeated. Active monitoring was set to a maximum of 30 seconds after transmitting its data. Throughout this period, a total of 30,019 messages were repeated. Despite reducing the transmission power to 2 W, the module failed to recharge adequately under cloudy and cold weather conditions. By December 6th 2021 the battery voltage had fallen below the critical level.

Incorporating predictive models for battery levels based on observed weather and voltage data could significantly enhance the operational efficiency of AtoN systems. By analysing historical patterns, it would be possible to forecast potential drops in battery voltage during extended periods of unfavourable weather conditions, such as cloudy or stormy days. Furthermore, an early warning system could be developed to alert operators when the battery level is projected to fall below a critical threshold. Such a system would allow for proactive maintenance and ensure continuous reliable operation, especially in remote or hard-to-access locations. By integrating weather forecasting with real-time voltage monitoring, these systems could optimise the recharging cycles and provide more accurate predictions about the battery's performance under varying environmental conditions.

4.1. Possibility of using inland AIS AtoNs as AIS repeater stations

Type 3 AtoNs can be utilised in repeater mode. However, it is important to consider the increased energy demands, as an AtoN in repeater mode is configured to transmit not only its own messages but also specific AIS messages (e.g., No. 6, 8, and 21) from other nearby AtoNs within its radio range. It does not repeat messages from vessels or other transponders. Based on the deployment plan, AtoN MMSI 267100006 was selected for testing in repeater mode.

The configured repeater mode parameters were as follows:

- Repetition of AtoN AIS messages No. 6, 8, and 21.
- No limit on the radius distance from which messages will be relayed.
- Repeat indicator (0..2), where 0 indicates the original AIS message, 1 indicates the first repetition, and so on. Set to 0.
- Monitoring interval for relaying messages set to 30 seconds.

The repeater AtoN must be active simultaneously with the AtoNs whose messages are to be relayed. During the testing period, three AtoNs were active: MMSI 267100008, 267100002, and 267100004. All AtoNs transmitted at the required intervals, and their signals were detected and repeated by AtoN 267100006. Only AtoN messages (No. 6, 8, and 21) were relayed, and no messages from vessels were repeated.

Table 4 shows a sample of received AIS messages, where repeated messages for all three AtoNs are included.

Message Reception Time	MMSI	Indicator
7-12-21 13:03:19	267100008	1
7-12-21 13:03:19	267100008	0
7-12-21 13:03:03	267100002	1
7-12-21 13:03:03	267100002	0
7-12-21 13:03:02	267100006	0
7-12-21 13:03:01	267100004	1
7-12-21 13:03:00	267100004	0

Table 4. Sample of Repeated Messages (Source: Authors).

An indicator value of 1 means that the message was repeated once, while 0 indicates the direct, original message. The quality of repetition is calculated as the ratio of the frequency of received direct messages to repeated messages. The first months of AtoN operations on the Slovak section of the Danube provided valuable insights regarding buoy placement, data collection, sensor performance, as well as experiences from unexpected changes in the Danube's flow caused by hydro-meteorological influences.

The evaluation of the repetition success rate is presented in Table 5 and is divided into two periods.

Message 21	MMSI	1	0	%	Distance [m]
November 25 – December 4, 2021	267100002	3742	3979	94.04	5441
Minimum voltage 11.4 V	267100004	4042	4239	95.352	2946
	267100008	4001	4142	96.60	2176
From December 4, 2021	267100002	1100	1334	82.46	5441
Voltage below 11.4 V	267100004	1171	1474	79.44	2946
	267100008	1067	1373	77.71	2176

Table 5. Evaluation of Repetition Success Rate (Source: Authors).

The first period spans the time from the activation of the repetition mode on November 25th 2021, to December 4th 2021, during which the AtoN with MMSI 267100006 had a sufficiently charged battery above 11.4 V.

The second period begins on December 4th 2021, when the voltage dropped below 11.4 V, and the battery could no longer recharge.

During the first period, the success rate ranged from 94% to 96%, which is comparable to standard AIS operations. In the second period, despite the depleted battery, the AtoN was still capable of relaying messages, achieving a success rate of 77% to 82%, which is excellent given the battery's condition.

The AtoN in repeater mode reliably transmitted messages from a distance of 5.4 km (between 267100006 and 267100002). Repeater mode can be effectively utilised in real-world operations out of the winter season.

4.2. Comparison of Physical and Synthetic AIS AtoNs

Based on five months of AIS AtoN operation on the Slovak section of the Danube, the advantages and disadvantages of using AIS AtoNs in regular operations are summarised in Table 6.

Aspect	Physical AIS AtoN	Synthetic AIS AtoN
Advantages	- Provides real-time data directly from the site, ensuring accurate information about the local environment. - Can include integrated sensors for additional environmental data (e.g., temperature, water depth), enhancing situational awareness. - Visible as a physical marker, aiding in navigation and increasing safety for vessels in the vicinity.	- No need for physical installation at the actual location of the navigational aid, as the AIS signal is generated from a shore-based station, reducing costs and logistical challenges at the deployment site. - Data can be generated and transmitted from remote locations, increasing flexibility and enabling coverage in hard-to-reach areas. - Can simulate multiple AtoNs without the need for corresponding physical structures, offering a scalable and efficient solution for monitoring large areas.
Disadvantages	- Requires installation and regular maintenance, which can be costly and time-consuming, especially in remote or hazardous locations. - Susceptible to environmental damage (e.g., storms, corrosion) and power issues, which can lead to operational downtime. - Limited to its physical location and cannot easily be relocated, reducing its adaptability to changing conditions or needs.	- Does not provide real-time physical presence, which may reduce its effectiveness as a navigation aid, especially in poor visibility conditions. - Dependent on accurate and up-to-date data inputs; errors in data can lead to inaccuracies, potentially compromising safety. - May not be as reliable in areas with poor network connectivity, which can affect the timely transmission of information.

Table 6. Advantages and Disadvantages of AtoNs (Source: Authors).

Based on the testing experience and the aforementioned advantages and disadvantages, the combination of a physical AIS AtoN and the specific type of buoy on the reference section of the Danube will require careful consideration of the conditions at the intended deployment site during regular operations.

A synthetic AIS AtoN does not have a physical device installed at the actual location of the aid. Instead, it digitally simulates the presence of a navigational aid by broadcasting AIS messages from a shore-based station. This allows for navigational assistance in areas where the physical deployment of an AtoN may not be feasible, but it still requires supporting infrastructure at the shore-based control station.

5. CONCLUSION

AIS AtoNs are pivotal in enhancing the safety, efficiency, and sustainability of inland waterway transport. Addressing challenges related to standardisation, maintenance, costs, and security is essential to fully realising their potential. Ongoing research and international collaboration will be crucial for overcoming these obstacles and advancing the widespread deployment of AIS AtoNs in inland waterways.

Assessment of AtoN Operation on the Pilot Slovak Section of the Danube:

- The deployed buoys exhibit varying vertical tilts in areas with different current flows, which can be mitigated through anchoring methods. However, a standardised anchoring approach is necessary to ensure buoy stability across the entire Danube stretch.
- Minor vertical tilts of the buoys do not affect the reliability of AIS communication.

- AIS communication on the reference section operates without issues. The selected reference stretch of the Danube is insufficient to demonstrate the suitability of these buoys for other sections of the river. In future investigation testing on additional stretches of the Danube is required for validation.
- During high water levels (e.g., Bratislava above 500 cm), operations are at risk due to increased occurrences of trees and other floating objects.
- The energy consumption of AIS modules during the specified period and on the reference section did not present any problems.
- Testing revealed that buoy placement in the area above the Harbor Bridge is considered risky during high water levels (above 450 cm, Bratislava).
- The use of some buoys as repeaters is problem-free during months with adequate sunlight. However, in practice, it is impractical to rely on external battery chargers during reduced sunlight conditions. Further testing is needed to assess battery capacity and transmission performance for illuminated buoys. This testing can be conducted under static conditions, outside of actual deployment in the navigation channel. This applies generally to all buoy types mentioned.

A model of water levels for the entire Slovak section of the Danube could significantly contribute towards optimising buoy placement. With precise current values at the buoy's anchoring location, it would be possible to better determine the required chain weight or other anchoring solutions to ensure vertical stability of the buoy. While the current research provides valuable insights into the operational performance of AIS AtoNs on inland waterways, future work could focus on two areas, critical for improvement:

- Design enhancements to minimise tilting and debris interference: future buoy designs could incorporate advanced anchoring systems or dynamic stabilisation technologies to minimise tilting, particularly in areas with strong currents or variable water levels. Additionally, the integration of protective features against debris, which is a frequent issue during high water events, would ensure greater operational reliability.
- Energy management for extended cloudy periods: given that cloud cover can be predicted for long periods of the year, future research should explore the use of larger batteries or alternative energy storage solutions. New battery technologies, such as lithium-ion or supercapacitors, could offer extended operational periods without external recharging. Implementing these solutions would mitigate the impact of low solar input, ensuring uninterrupted operation during winter months or extended cloudy periods.

Standardising these design features could help to establish global guidelines for AtoNs used in inland navigation, benefiting both the operational efficiency and regulatory harmonisation across regions.

CONFLICT OF INTEREST

The authors have declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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