applied sciences

Article

Functionality of the Search and Rescue Transponder (SART) in Maritime Search and Rescue Actions

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Abstract: In this article, the authors present contemporary problems in search and rescue operations at sea. The research focuses on the detection of the SART (Search and Rescue Transponder) device. This device is used to call for help and assist the rescuing vessel in tracking. Issues with their functionality may reduce the likelihood of finding a survivor. The authors designed an experiment to assess the effectiveness of using the device. The research conducted is a real-world experiment that involved a ship radar, a liferaft, a SART device, and a radar reflector. The experiment consisted of multiple trials to detect, locate, and track the device, as well as to assess the radar image features. Four scenarios were developed, considering different distances and radar settings. Performance evaluation indicators were also developed. The results are presented both graphically and numerically. A brief discussion of the obtained results and concise conclusions are provided. Along with the research findings, recommendations for the use of SART and radar on ships are also presented, as well as recommendations for improving training. The results are applicable to improving the effectiveness of SAR operations.

Keywords: search and rescue; radar transponder; detection; SART; survivor

Academic Editors: Atsushi Mase and Amerigo Capria

Received: 1 December 2024
Revised: 9 January 2025
Accepted: 16 January 2025
Published: 20 January 2025

Citation: Malyszko, M.; Wielgosz, M.; Rzepka, B. Functionality of the Search and Rescue Transponder (SART) in Maritime Search and Rescue Actions. *Appl. Sci.* **2025**, *15*, 996. https://doi.org/10.3390/app15020996

1. Introduction

Modern maritime search and rescue operations involve several stages. The most significant of these are the analysis of large amounts of navigational, hydrometeorological, and traffic monitoring data, the calculations associated with a search or rescue plan, and the execution of the operation. Sophisticated systems and equipment, as well as modern technology, are used to support the operations. SAR (search and rescue) services mainly conduct these operations, but non-rescue vessels, including cargo, passenger, specialized, fishing, and recreational types, may also participate. Searching at sea carries significant risks. The probability of locating survivors depends on the accuracy of data on the coordinates of the accident, time of the accident, weather conditions, correct calculation of the reference position, knowledge of the type of object searched for, and many other data. The use of detection aids by survivors gives them a better chance. However, these devices must be operated correctly. Rescue vessels must also use their equipment properly to detect survivors. As statistics show, more than 80% of maritime accidents are related to the human element. Errors made by ship crews are often caused by the use of inappropriate procedures or insufficient competence. Training and increasing seafarers' knowledge are therefore essential in improving safety at sea.

One of the most effective devices for search and rescue operations at sea is the SART radar transponder—Search and Rescue Transponder. The SART is a portable X-band

(9 GHz, 3 cm wavelength) device that operates at standard marine radar frequencies. It is used to transmit a distress signal passively. When it is turned on, it waits to be activated by surface or airborne units' radar waves, and it reflects the signal. Marine SARTs are available as basic radar SARTs or the more advanced GNSS-supported AIS-SARTs (which also operate within the Automatic Identification System—AIS). A SART can be operated directly from the deck of a sinking ship or from a survival craft, such as a lifeboat or liferaft. For the best detectability, it is recommended that the minimum height above sea level be 1 m. When activated by radar waves, it creates a series of dots (echoes) on the radar display. The closest of these echoes is the approximate position of the transponder. The radar image changes depending on the distance from the radar (Figure 1). To receive the SART signal, a properly adjusted radar is required. The most important radar settings include range, operating mode, display mode, pulse length, and clutter filter.

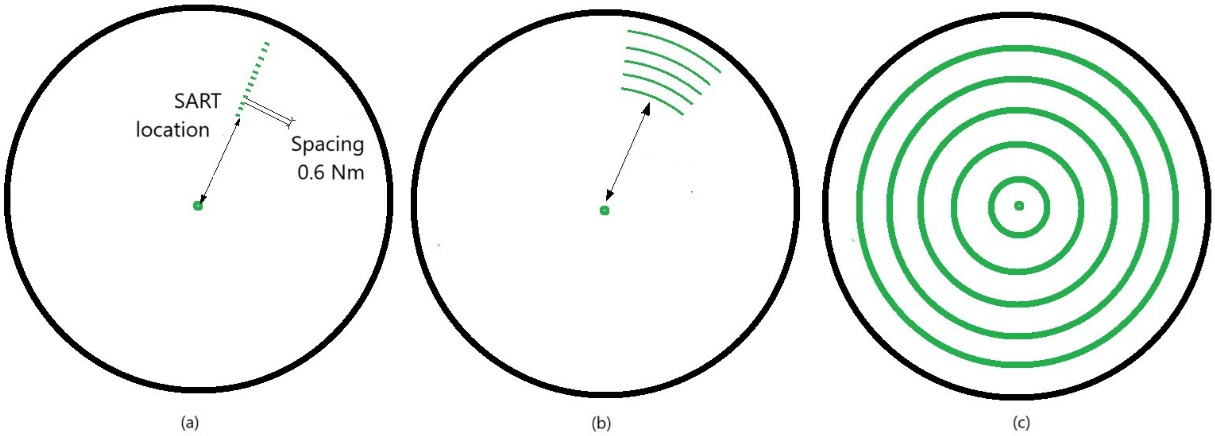

Figure 1. SART image on the radar screen depending on the distance from the vessel. (**a**) Distance of 5–6 Nm, radar range 12 Nm; (**b**) Distance of 2–3 Nm, radar range 6 Nm; (**c**) Distance < 1 Nm, radar range 6 Nm.

The SART is not a device that ships use on a daily basis; it is an emergency tool specifically designed for emergency situations. As such, detailed knowledge of its operation may be limited. A visual check of the device is carried out by the navigation officer once a month. However, the device is usually tested only once a year. More frequent testing is not recommended due to the risk of battery drainage.

The test involves turning the device on and observing the response signal on the ship's radar. The distance between the device and the radar antenna is generally not large during such a test, as it is constrained by the size of the vessel. While the device can be placed at the edge of the vessel (e.g., stern or bow), in most cases, the distance will not exceed 100 to 200 m. At such short ranges, the navigator will typically observe full circles. It is not possible to test the device under different conditions.

When abandoning a ship in an emergency, seafarers must be familiar with the procedures, take the SART device with them to the survival craft, and ensure the device is properly fitted. For the device to be detected, vessels passing nearby must have their radars properly tuned. Any errors made by the radar operator or the survivor may reduce the effectiveness of the device.

Such a situation occurred recently. A case was reported in which the SART device could not be detected during a real-life emergency situation involving a person calling for help. Ships were passing very close by but were unable to receive the device's signal. An investigation was then conducted, revealing issues with the radar settings (the automatic tuning option limited the signal reception) and the height at which the device was placed. These factors are crucial for conducting search and rescue operations and for the chances of saving a human life. It is essential to properly educate maritime navigators on the use of radars and sailors in general on the use of the SART device in emergency situations.

The device's performance and physical characteristics are verified by the manufacturers. However, conducting experiments with ships under different weather conditions or settings is not common practice, as it is both costly and time-consuming. Experiments are sometimes conducted in the laboratory or on land, which means that the influence of many factors is often neglected. The most commonly studied element in scientific research is the detection range of the SART device and the signal strength. Other elements are rarely studied. There is little to no research on the relationship between radar settings and the presence of a radar reflector (other aid supporting the detection of the object by radar) on a survival craft.

There is a gap in scientific research. The authors prepared and conducted an experiment addressing some of the issues related to the effectiveness of the SART. They developed a method and established effectiveness indicators. The method includes both a qualitative and a quantitative assessment of the data. Performance indicators include signal detectability, echo distinctiveness, response signal shape, interference level, and radar image readability. This work contributes to the advancement of the field of maritime search and rescue. The results are also valuable for officers and sailors, as they provide knowledge on potential issues. Practical knowledge, supported by theory, is crucial for ensuring safety at sea and can be used to improve seafarers' competence. The results are also valuable for optimizing SAR (search and rescue) operations.

Below are some references to the requirements, test reports, and scientific papers related to the use of the SART device in search and rescue actions.

Planning and conducting SAR operations are based on the jointly developed International Aeronautical and Maritime Search and Rescue Manual by IMO and ICAO (vols. 2 and 3) [1,2]. On ships, these procedures are additionally supported by publications such as ALRS vol. 5 GMDSS [3]. The requirement for equipping ships with these devices (one or two) is established by the SOLAS Chapter III convention [4]. The latest operational standards for SART devices are contained in the IMO MSC.510(105) resolution [5]. The foundations of modern SAR operations are presented in [6].

The results of studies on detectability range, antenna height, and the effect of obstacles (e.g., liferaft components) obscuring the device are presented in [7]. It was emphasized that the impact of the radar reflector on the SART's detectability by the ship's radar was not studied. However, it was noted that detection performance may be reduced.

The case study and results of the experiment using the radar's automatic features are discussed in [8]. The performance of SART devices in actual sea weather conditions is presented in [9–11].

The use of SARTs and detection issues are discussed in [12]. The authors also propose modifications to the device to enhance detection efficiency through other methods. The authors of the experiment [13] conducted comparative tests of the SART 9 GHz, AIS-ART, and EPIRB involving aircraft. The SART was mounted at a height of 1 m. The experiment focused exclusively on testing the detection distance with altitude variations between 1000 and 20,000 feet.

A comparison of the detectability of the SART 9 GHz with other devices using satellite systems or VHF waves is presented in [14]. This research examined the maximum detection distance of the devices at different altitudes. A description and study of the differences in signal strength between traditional SART and circular polarization SART, as well as the potential for reducing the size of the device, are discussed in [15]. The author of the paper [16] highlights the challenges of detecting the SART device and the reduced effectiveness in difficult weather conditions, especially in rough seas. He also mentions the difficulties of using both auto and manual settings, which can be ineffective, particularly at short distances from the SART. Research and discussions on the optimal shape of a radar reflector to enhance radar wave reflectivity are presented in [17].

An innovative solution for SART devices, referred to as SART-DMOM, has been proposed for use on small vessels (originally, mainly fishing vessels) [18]. The basic principles of use, technical and operational parameters, testing procedures, and the evolution of testing devices are presented in [19].

After the implementation of the AIS system, the introduction of requirements and the installation of devices on ships, the potential for its use in SAR was recognized, leading to the emergence of AIS-SART devices, which add AIS system transmission to the transponders. The use of the AIS system in maritime search and rescue is presented in [20]. This significantly improved the detectability of transponders, including small commercial and recreational units, by increasing the range to the VHF range. The proposal for new advanced real-time SART is presented in [21]. Tests on the operability of the SART device and its dependence on antenna height are discussed in [22]. In this study, the authors followed the instructions for the SART device [23].

The problem of radar interference and sea clutter, as well as the possibilities of their reduction, are discussed in this paper [24]. Research on radar interference and improved object detection is presented in [25].

As the literature review indicates, the SART device has many advantages, but there are also known issues with its effectiveness under certain conditions. The authors conducted a real-world experiment to verify whether these problems occur and to what extent the effectiveness of the SART may be compromised.

The experiment was conducted using specific equipment and under particular hydrometeorological conditions. The height of the radar antenna, the radar model, the SART device model, the altitude of the SART device, and weather conditions all influence the results and may also introduce certain limitations. However, conducting an experiment according to specific rules allows for interesting analyses and conclusions to be drawn.

Despite some constraints, the results are an important contribution to maritime search and rescue research. The data will serve as a basis for similar studies on a larger scale, potentially providing a benchmark for comparison. In the educational field, the experiment helps in understanding the subject during the training of maritime personnel. All of this is aimed at improving the effectiveness of saving lives at sea.

2. Materials and Methods

A typical marine radar transmits a high-power pulse stream at a fixed frequency in the 9 GHz band (9.2–9.5 GHz). It collects the echoes received at the same frequency and displays them. The SART device operates by receiving a pulse from the search radar and sending back a series of pulses in response, which the radar then displays as normal echoes. While the SART is being interrogated by the search radar, it continuously scans the radar band for radar signals. When the range closes so that fast sweep responses are detected, the first dot of the SART response displayed will be no more than 150 m distant from the true location of the SART. When the range is such that only slow sweep responses are detected (range approximately greater than 1 nautical mile), the first dot of the SART response displayed may be as much as 0.64 nautical miles beyond the true position of the SART. The radar-SART may be triggered by any X-band radar within a range of approximately eight nautical miles (15 km). In stand-by mode, the SART unit will wait 96 h for activation. Once activated, the transmission time is a minimum of 8 h.

The radar settings affect its detection functions. The radar must be properly prepared and tuned. The condition of the radar is also crucial for proper image display. The accuracy of the displayed image depends primarily on the condition of the oscillator (magnetron), power, frequency band, resolution, sensitivity, gain, noise reduction, pulse length, and range. To assess the radar's transmission and reception power, the performance test is used, among other methods.

Its primary function is to receive reflected signals from obstacles (objects), allowing the navigator to make anti-collision decisions. Radar settings can be adjusted manually or automatically. In automatic mode, the radar adapts to changing weather conditions, using features such as gain or clutter filters (e.g., sea and rain clutter filters) to eliminate interference from sea waves or rain, thereby improving the radar image quality. However, if the radar image is cleared too much, small objects will also be removed. Figure 2 shows the appearance of the radar screen along with the control panel.

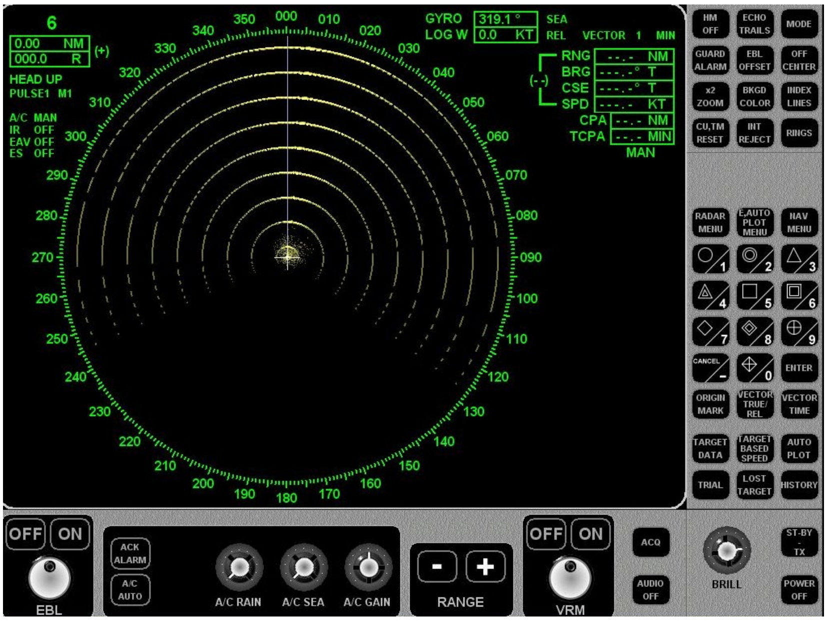

Figure 2. SART image on the radar [ECDIS Simulator NaviTrainer 5 Wartsila, Helsinki, Finland].

The ability to detect an object also depends on its size. It is practically impossible to detect small objects, such as people in the water. Depending on the distance, a liferaft may be detectable. To enhance the signal, the user of the liferaft should use a radar reflector. The radar reflector works by reflecting radar waves back towards the source. Unlike the SART device, the radar reflector has no mechanism or electronics (Figure 3).

Figure 3. Radar reflector (**left**) and SART (**right**) placed next to each other on the liferaft.

During a certain accident in 2022 [8], the survivor used the SART, but the device was not detected by any of the four ships' radars in the vicinity. The survivor was floating on the water's surface and did not use the telescopic extension; instead, he held the device upside down with his hands. This could have affected the device's range. The person was eventually rescued after several hours. An inspection of the device was conducted, and it was found to be operational and in good condition. The vessel's X-band radar settings were also checked, and it was found that certain settings, such as Auto mode, significantly reduced the SART device's detectability. No dots or circles were displayed on the screen, so the user was not notified of the SART detection.

To study the impact of radar settings, the authors conducted a large-scale experiment in real sea conditions using a physical SART device and marine radar. The main objective of the experiment was to observe changes in the radar image when receiving the SART device's response. The specific objectives were:

1. To verify the detectability of the device under different conditions (varying distances, radar settings, and the presence of the radar reflector);
2. To determine the ability to acquire and track echoes under different conditions.

The research was conducted in the Bay of Pomerania in the Baltic Sea (Figure 4) in 2024, at geographic coordinates $\varphi = 54°36.8'$ N; $\lambda = 14°41.6'$ E. The search target was a liferaft equipped with a S4 Rescue SART device (McMurdo Portsmouth, UK). The SART device was positioned 1.5 m above the sea surface. A 15-m-long vessel equipped with an X-band Raymarine radar was used for the survey. The radar antenna was mounted at a height of 6 m above the sea surface, while the observer's eyes were positioned at a height of 3 m. The vessel used in the experiment is a search and rescue type, actively engaged in daily service. This medium-sized vessel is primarily designed for search operations, survivor recovery, casualty transport, and towing. It is optimally equipped for effective operations, particularly for search activities. The antenna height is not significant and differs from that of typical cargo or passenger vessels, which may affect the reception of the SART response signal.

Figure 4. Area of research (red rectangle).

The external conditions during the experiment were as follows: sea state 2, wind from the northeast at 5 m/s, very good visibility, a temperature of 19 °C, and a partly cloudy sky.

During the experiment, four scenarios were tested (Table 1). The scenarios took into account different radar settings (manual and automatic) and the use of a radar reflector. Each scenario was performed six times, with the rescue vessel and the search target deployed at varying distances ranging from 0.2 to 4 nautical miles.

Table 1. Main assumptions of the scenarios.

Scenario	Radar Settings	Radar Reflector	Distance [Nm]
Scenario 1	Manual	No	0.2–4
Scenario 2	Auto	No	0.2–4
Scenario 3	Manual	Yes	0.2–4
Scenario 4	Auto	Yes	0.2–4

Conducting various scenarios allowed each combination of settings to be tested separately. Situations involving non-compliant installation of the device were avoided during the experiment. According to the manufacturer's instructions, the SART device should not be used at a height of less than 1 m above the water surface. During the tests, the device was placed at a height of 1.5 m and no farther than 6 nautical miles from the ship. The scenarios were conducted following the procedure shown in Figure 5.

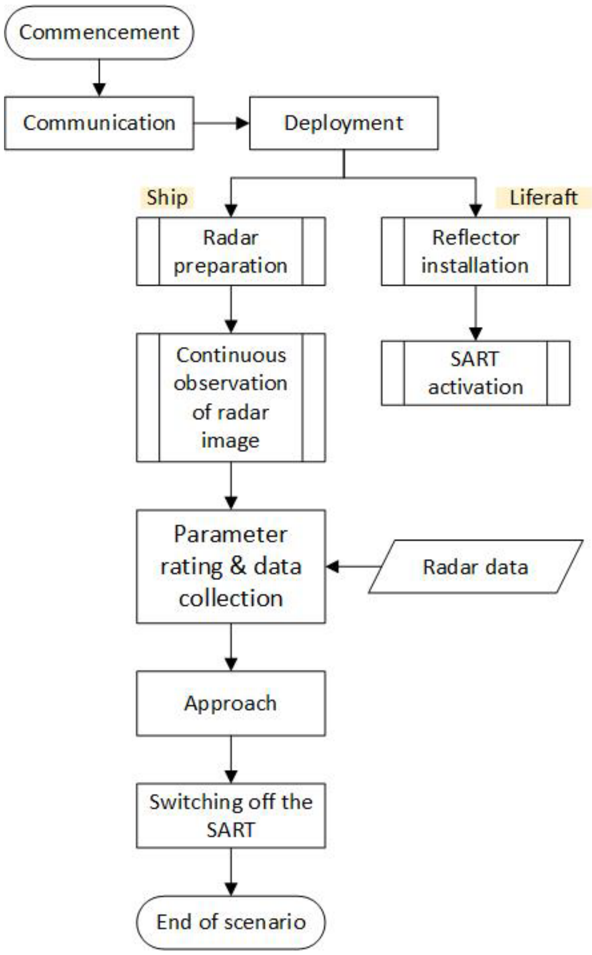

Figure 5. Experiment procedure.

The stages of the procedure are a key part of any scenario. Maintaining the order of the phases ensured that the experimental conditions were repeatable. Descriptions of the stages are provided in Table 2. A detailed explanation is given below the table.

Table 2. Stages of the experiment.

No.	Stage	Description
1	Communication	Rescue vessel and support boat communicate by VHF radio.
2	Deployment	The surface units are positioned at appropriate distances.
3	Radar settings	The radar is to be prepared according to the correct procedure, adapting to external and navigational conditions. The navigator selects manual and automatic settings. The radar antenna is located at a height of 6 m.
4	SART activation	The SART device is correctly placed at a height of 1.5 m on the liferaft and activated as instructed. A radar reflector will also be used in some scenarios.
5	Radar observation	The navigator waits for the SART response by observing the radar image. Once detected, the navigator analyzes the signal, determines the parameters (distance, bearing), and evaluates the radar image features.
6	Approach	During the approach, the navigator observes changes in the radar image, identifies the moment of interference, and assesses the possibility of acquiring and tracking the echo.
7	Switching off	The device is switched off when its position is reached.

The ability to communicate is crucial for safety during work at sea. The assisting boat and the rescue vessel must move away from each other. When the planned distance is reached, the rescue vessel gives the command to activate the SART. Communication procedures include the communication channel, backup channel, commands, responses, and a "code word" for aborting the exercise in case of an emergency. The crews of both vessels are equipped with individual lifesaving devices. Detection and tracking of the SART device occur at different distances. In the experiment, each scenario was performed six times at distances ranging from 0.2 to 4 nautical miles. Radar interference or lack of detection will be assessed in this study.

As explained earlier, the manual option involves the user adjusting the radar to the prevailing conditions, while the auto mode adjusts these settings automatically.

The purpose of a radar reflector is to amplify the echo signal of an object (in this case, a liferaft) detected by radar. The radar reflector consists of several sections arranged perpendicular to each other. A radar reflector is provided with the liferaft equipment. In an emergency, the survivor should mount the device on top of the raft. The SART device is part of the ship's equipment and should be taken by the crew before abandoning the ship. It should be mounted as high as possible. During the experiment, activation and deactivation of the SART device occurred on command. The navigator on the vessel uses radar to detect the device.

The navigator then tracks the echo of the liferaft, determines the echo parameters, sails the rescue vessel to the object, and observes the changes in the radar image. Figure 6 presents the approach to the liferaft.

The evaluation of the results of the experiment was conducted both qualitatively and quantitatively. The qualitative assessment involves the navigator visually examining four components and rating them on a scale. The qualitative method is applicable here because it reflects the natural use of the radar by the operator.

The experiment has its limitations due to the conditions under which it was conducted. These conditions include specific weather conditions and the use of particular equipment (radar model, SART device model, height of radar antenna placement, and position of the SART device). The conditions of the experiment may affect the results.

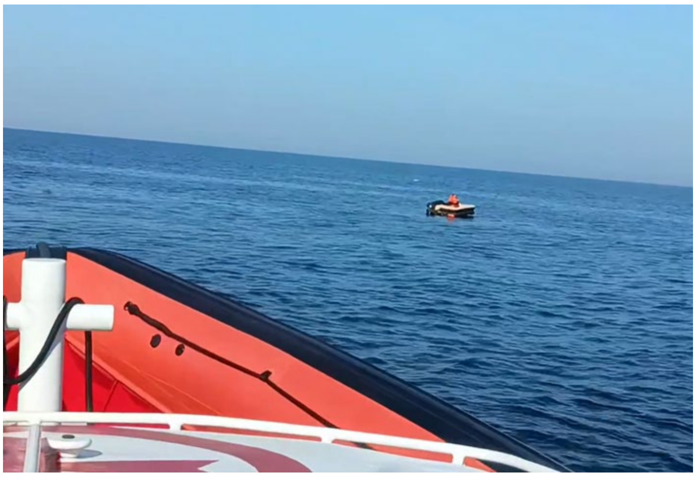

Figure 6. Research field—liferaft with SART in the proximity of the searching unit.

The most important element of the experiment is the device that receives the SART signal: the marine radar. As the condition of the radar device and its settings are crucial to its ability to display the image correctly, the radar must be properly maintained and tested. Before using the radar in the experiment, a performance test was conducted, and the magnetron parameters were checked. Settings such as range, gain, and clutter were adjusted according to the navigational and weather conditions. The navigator adhered to all procedures and best maritime practices for radar preparation and operation. This ensured maximum data reception.

The study examined the following components:

(a) Detectability of the SART device by ship radar (A1);
(b) Distinctiveness of the liferaft echo on the radar image (A2);
(c) Compatibility of the response signal shape (A3);
(d) Interference in the radar image (A4).

A two-level scale was used for the first three components. The assessment involves determining whether the feature is present (rating: 0 points for a negative evaluation, 1 point for a positive evaluation). The two-level scale specifies that the minimum criteria are met as follows: for component A1 (detectability)—detected/not detected, for component A2 (distinctiveness)—echo visible/not visible, and for component A3 (shape)—compatible/incompatible. For the fourth component, A4 (interference), a three-level scale was used. The following ratings are used for assessing the occurrence of interference: weak (0 points), medium (1 point), and strong (2 points). Weak interference means that the radar image is clear and easy to interpret. Moderate interference means that the interpretation of the image becomes difficult. Strong interference means that important data cannot be read or actions cannot be performed (e.g., acquiring an object for tracking). Table 3 provides the main information on the rating method.

In addition, at each distance interval, the navigator will assess the overall clarity of the radar image and express it as a percentage. To assess the applicability of the SART device, the effectiveness of a component will be determined.

Effectiveness is a measure of success and is calculated as the ratio of the number of positive occurrences to the total number of attempts (Formula (1)).

$$W = \frac{E}{N} \tag{1}$$

where,

W—effectiveness;

E—number of positive assessments;
N—total number of attempts.

Table 3. Assessment of radar image features.

Label	Component Description	Scale	Evaluation Range	Evaluation Description
A1	Detectability of the SART device by ship radar	Two-level	0–1	0—not detected 1—detected
A2	Distinctiveness of the liferaft echo on the radar image	Two-level	0–1	0—not visible 1—visible
A3	Compatibility of the response signal shape	Two-level	0–1	0—not compatible 1—compatible
A4	Interference in the radar image	Three-level	0–2	0—weak 1—medium 2—strong

In this way, the effectiveness of two parameters, A1 and A2, will be determined. The effectiveness of the shape will be calculated as the arithmetic average of the three detection ranges (Formulas (2) and (3)). According to the SART user manual, at distances of 5–6 Nm, the navigator should observe dots; at distances of 2–3 Nm, the navigator should observe arcs; and at distances of less than 1 Nm, the navigator should observe concentric circles. These expected signal shapes will be studied in the following ranges: 4 Nm and greater, 1–3 Nm, and less than 1 Nm. The amount of interference (A4) will be evaluated separately as a function of the relationship between the level of interference and the distance and will be shown in the graph.

$$W_s = \frac{W_n}{n} \tag{2}$$

$$W_n = \sum_{i=1}^{n} \frac{E_i}{N_i} \tag{3}$$

where,

W_s—effectiveness of shape compatibility;
W_n—effectiveness of shape compatibility in the i-range;
n—number of ranges;
E_i—number of positive assessments in i-range;
N_i—total number of attempts in i-range.

The procedure discussed above for conducting the experiment and analyzing the results will allow the study to achieve its objectives. The study, conducted at varying distances and with different settings, will primarily verify the impact of the marine radar image on the success of search and rescue operations.

It should also be noted that when a ship approaches an object after detecting a signal but is unable to locate it, a search plan should be developed in accordance with the IAMSAR Manual. This is a requirement of the International Maritime Organization (IMO). The manual provides guidelines, recommendations, and advice for search and rescue operations at sea. One key element of the search plan is defining parameters for the search pattern, such as track spacing during the scan. This spacing must be optimized to ensure the detection of the object. Calculations [2] are made using Formula (4).

$$S = S_u \times f_w \tag{4}$$

where,

S—corrected sweep width;
S_u—recommended track spacing;
f_w—weather factor.

For a six-person raft, the track spacing of 2.5–6.9 Nm is recommended, depending on the meteorological visibility in the area (3–20 Nm). This applies if the wave height does not exceed 1 m. For wave heights of 1–1.5 m, these figures should be reduced by a weather coefficient of 0.9. If the wave height exceeds 1.5 m, it is recommended to reduce the spacing by a factor of 0.6. This gives a corrected sweep width of 1.5–4.1 Nm (depending on the meteorological visibility in the area in the range of 3–20 Nm). All these guidelines, however, do not take into account the height of the observer's eyes. The size of the vessel and the height of its superstructure determine the position of the observer. On boats, this elevation is about 1–2 m above the sea surface. On small vessels, it is usually 3–10 m. On large vessels, it is even above 50 m. The elevation of the observer's eyes is an important aspect affecting the effectiveness of the search action, according to the authors.

Figure 7 shows a plot of the corrected sweep width for two objects: a man overboard (MOB) on the water surface and a six-person raft. The variable factors are the weather factor f_w, expressed by wave height in meters, and the visibility range, expressed in nautical miles. The track spacing for searching for a person in the water ranges from 0.4–0.7 Nm for wave heights below 1 m, and from 0.1–0.2 Nm for wave heights above 1.5 m. In this case, more restrictive weather coefficients are applied (0.5 and 0.25, respectively). Spotting a small object, such as a person (usually only part of the body is visible above the water surface, e.g., the head or chest), is typically very difficult for the observer. Therefore, the use of a device to support tracking and locating is crucial, especially in conditions of reduced visibility. Table 4 presents the technical data of the SART device used [23].

Table 4. Technical specification of SART used for research.

Item	Details	
Frequency	9.2–9.5 GHz	
Polarization	Horizontal	
Sweep rate	5 µs per 2000 MHz nominal	
Response signal	12 sweeps	
Form of sweep	Forward	7.5 µs ± 1 µs
	Reverse	0.4 µs ± 0.1 µs
Pulse emission	100 µs nominal	
Effective Isotropic Radiated Power (EIRP)	>400 mW (+26 dBm)	
RX sensitivity	Better than −50 dBm (0.1 mW/m)	
Duration	96 h in stand-by condition followed by a minimum of 8 h of transmission while being continuously interrogated with a pulse repetition of 1 kHz	
Temperature range	Operating: −20 °C to +55 °C	
Recovery time	Following excitation 10 µs or less	
Antenna height	Greater or equal to 1 m	
Response delay	0.5 µs or less	
Antenna beam	Vertical: ±12.5 degrees Azimuth: Omnidirectional to ±2 dB	
Weight	SART complete: 530 g	
Buoyancy	Buoyant	

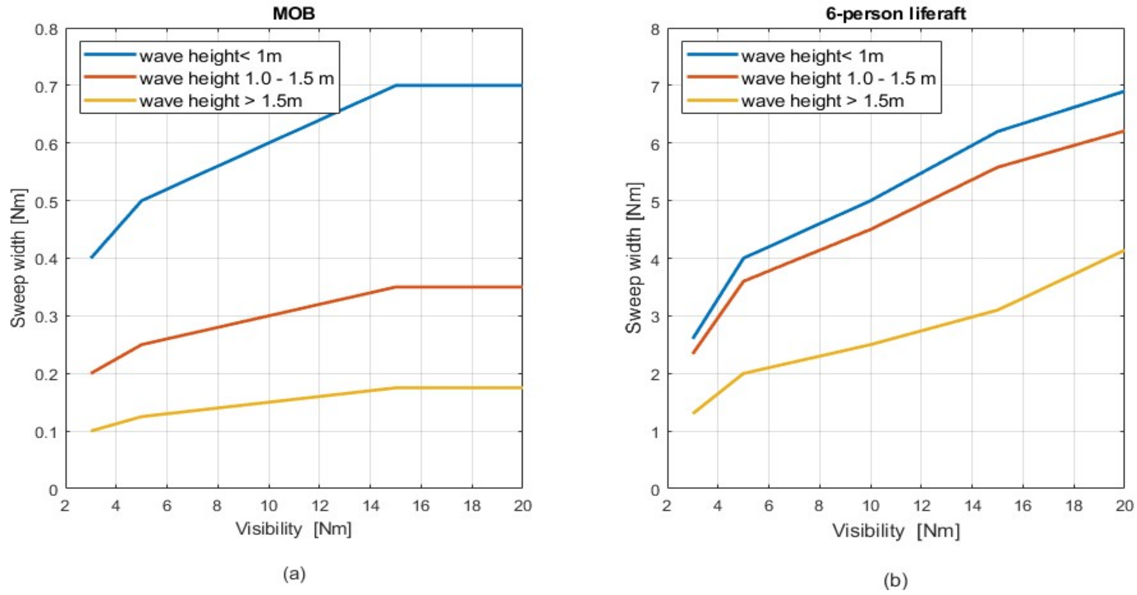

Figure 7. Corrected sweep width for searching in different weather conditions: (**a**) person in water (MOB); (**b**) liferaft.

3. Results

The results of the study are summarized in Table 5. The first column contains the deployment distance, the second column indicates the component labels and columns 3–6 contain the navigator's assessments for each scenario. A total of 24 trials were conducted and rated.

Table 5. Overview of the results.

Distance	Label	Scenario 1	Scenario 2	Scenario 3	Scenario 4
4 Nm	A1	1	1	1	1
	A2	1	1	1	1
	A3	1	1	1	1
	A4	0	0	0	0
3 Nm	A1	1	1	1	1
	A2	1	1	1	1
	A3	0	0	0	0
	A4	0	0	0	0
2 Nm	A1	1	1	1	1
	A2	1	1	1	1
	A3	0	0	0	0
	A4	0	0	0	0
1 Nm	A1	1	1	1	1
	A2	1	1	1	1
	A3	0	0	0	0
	A4	0	0	0	0
0.8–0.6 Nm	A1	1	1	1	1
	A2	0	0	0	0
	A3	1	1	1	1
	A4	2	2	2	2
0.6–0.2 Nm	A1	1	1	1	1
	A2	0	0	0	0
	A3	0	0	0	0
	A4	2	2	2	2

In the first part of the experiment (Scenario 1), the radar was set up manually, and SART devices were placed at distances of 4, 3, 2, 1, and twice at less than 1 nautical mile.

Each time, the appropriate functions were used to adjust the radar. The radar range was changed (from 12 to 1.5 nautical miles) to ensure that the response signal was displayed.

At a distance of 4 Nm, a signal from the SART was received (A1 = 1), and the visibility of the echo, as well as the compatibility of the expected shape, received a positive evaluation (A2 = 1; A3 = 1). The intensity of the interference was assessed as weak (A4 = 0).

At distances of 3, 2, and 1 Nm, a signal was also received, and the liferaft echo was visible. Both parameters received positive assessments (A1 = 1; A2 = 1). The SART response signal appeared as stretched echoes, but they did not form arcs. Such a response signal from the SART device is recognizable to the radar operator and indicates detection of the device, but it is not entirely consistent with the theoretical appearance of the echo. For this reason, this parameter was assessed negatively (A3 = 0). The intensity of the interference was assessed as weak (A4 = 0).

For illustrative purposes, sample photos of the radar screen are shown in Figures 8–11. Figure 8 shows the radar image after detecting the SART device at a distance of 2 Nm. The photograph is divided into two parts: the left part shows the electronic chart, while the right part displays the radar image. The current radar settings are manual, with a radar range of 6 Nm. The ship is located at the center of the radar image, which is oriented towards the north. The bow of the ship is pointing towards 316°. To the south of the ship, an echo from the shoreline is visible, extending from east to west. The echoes from the objects are marked with diamonds.

Eight characteristic points (echoes) are displayed, indicating the detection of an operational SART device at a bearing of 338° relative to one of the echoes.

Figure 9 shows the radar image at a distance of 1 Nm. The series of response signals is stretched but does not form the expected wide arcs. It is possible to acquire a liferaft echo for tracking. The current radar settings are manual, with a radar range of 3 Nm, a cantered image, and relative motion.

In each trial, when the vessel approached within less than 1 Nm, the response echo suddenly formed concentric circles, as stated in the instructions (Figure 10). It was no longer possible to isolate the liferaft echo from the radar image. The interference was very strong.

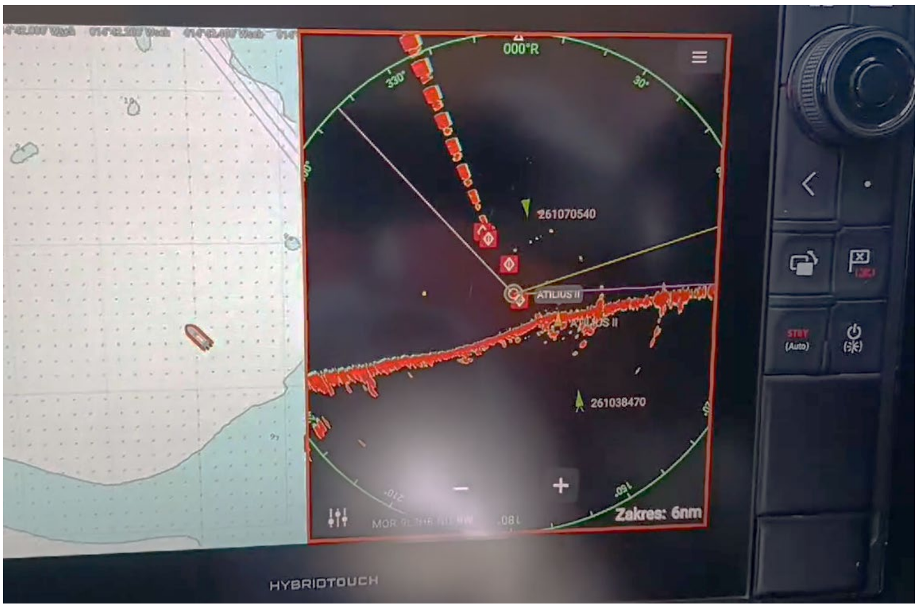

Figure 8. Radar screen showing the SART response signal at 2 Nm.

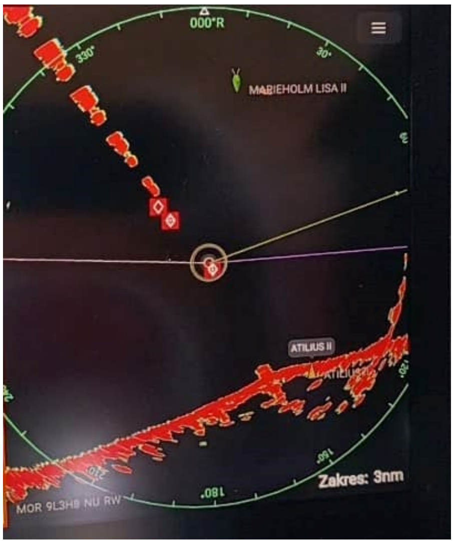

Figure 9. Radar screen showing the SART response signal at 1 Nm.

Figure 10. Radar screen showing the SART response signal at 0.6 Nm.

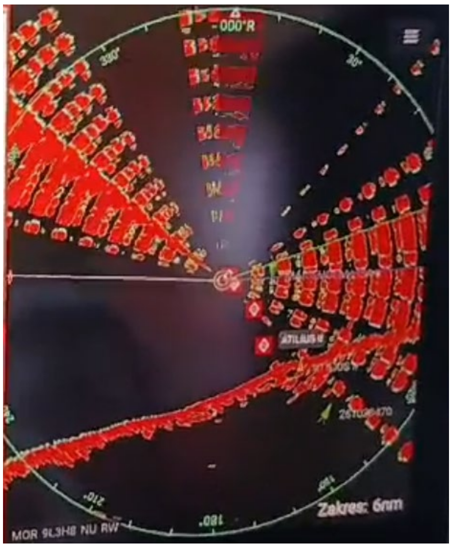

Figure 11. Radar screen showing the SART response signal at 0.2 Nm.

When attempting to detect the device's signal at short distances (0.2–0.6 Nm), the radar image took various forms, making it impossible to clearly determine the bearing of the object (Figure 11). However, the signal was detected every time.

Similar results were obtained for all other scenarios (Scenarios 2, 3, and 4). This indicates that there was no significant effect of the automatic radar settings or the presence of a radar reflector on the detection rate of the SART signal under the experimental conditions studied. The auto mode function adapts to weather conditions. During the research, these conditions were relatively favorable. It can therefore be assumed that the auto settings for sea or rain clutter were set to very low values. The reduction of interference from waves or wind was not needed, and the radar only eliminated it to a minor extent.

The effectiveness calculations for A1 (detectability) and A2 (echolocation) were made according to Formula (1). For this calculation, 20 trials were used (four trials at a distance of 4 Nm, four trials at a distance of 3 Nm, four trials at a distance of 2 Nm, four trials at a distance of 1 Nm, and four trials at a distance of less than 1 nautical mile).

The results of the calculations are shown in Figure 12. The device signal detection effectiveness (A1) is 100%. All attempts across all distance ranges were successful. The echo distinctiveness effectiveness (A2) during the signal detection moment (location of the liferaft) is 80%. Attempts to separate the echo were not possible in one distance range (the closest to the device). It should be noted that when approaching an object with an already detected SART signal and when the signal changes into circles, it was not possible to distinguish the echo every time. Therefore, the effectiveness drops from 80% to 0% at this point.

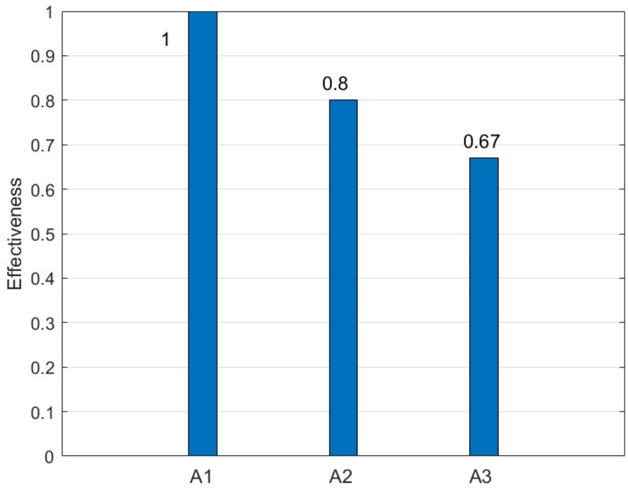

Figure 12. Effectiveness of the SART device.

The effectiveness calculation for A3 (shape compatibility) was made according to formulas (2) and (3) for three distance intervals: 4 Nm and more (expected dots), 1–3 Nm (expected arcs), and less than 1 Nm (expected circles, according to the instructions). The shape effectiveness is 66.67%. Shape incompatibility was noted in the middle-distance range (between 1 and 3 Nm).

The amount of interference (A4) associated with the reception of the SART device signal is shown in Figure 13. At distances greater than 1 Nm, interference is described as weak. The reception signal of the SART device covers the image only along the bearing line, which may still cause some difficulty in assessing the echoes of other ships or objects on the same bearing. In general, these can be described as minor but require special attention from the navigator. At ranges below 1 nautical mile, there is a rapid decrease in image readability. The entire screen becomes covered by extensive rings of echoes.

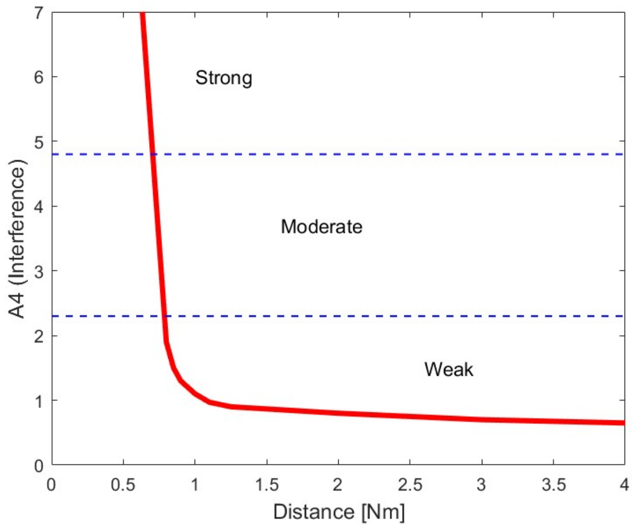

Figure 13. Amount of radar image interference depending on the distance of the SART device.

In each trial, the navigator assessed the percentage of image clarity. The results of this assessment are shown in Figure 14. It can be seen that the image quality remains good (above 80%) most of the time. The SART response signal occupies a narrow sector of the radar image when the device is detected at distances greater than 1 nautical mile. As the vessel approaches, the amount of interference increases significantly. The diagram also includes an assessment of the ability to distinguish life raft echoes, which decreases significantly at distances below approximately 0.8 nautical miles.

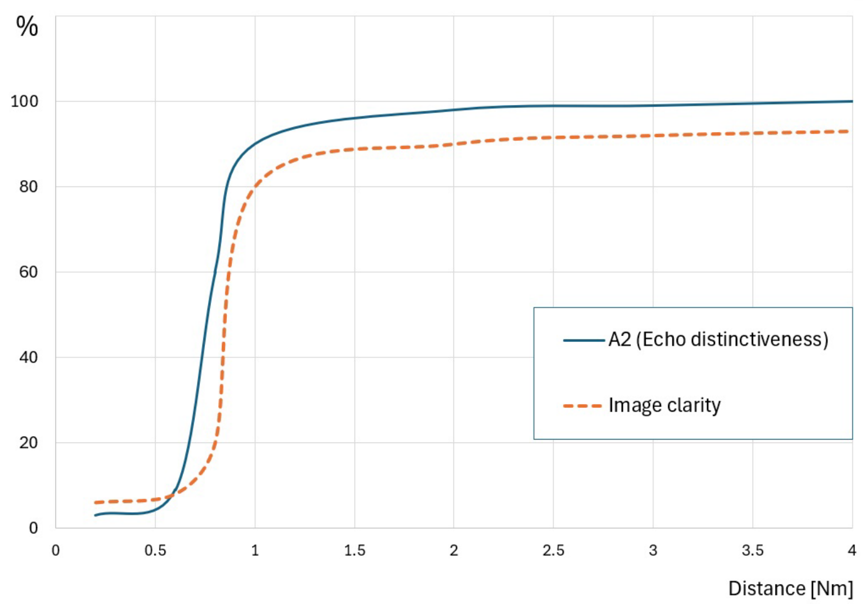

Figure 14. Assessment of image clarity.

4. Discussion

The maritime industry is a specific field focused on the practical use of equipment. Multiple studies are necessary to improve its performance and reduce errors.

Research conducted at sea, far from shore, carries certain risks. Its execution requires the involvement of various forces and resources. First, a surface vessel, properly equipped and manned, is necessary. Second, it is necessary to place a SART device in the water area. For this purpose, another assistance boat, also properly equipped and manned, is required.

It is crucial to establish proper procedures, especially for communication, regarding the conduct of the exercise and possible interruptions in the event of an emergency.

Sea experiments are highly influenced by environmental conditions. The objects under study are on the surface and are subjected to external forces such as waves, wind, and currents. It is challenging to ensure the repeatability of conditions. Usually, these conditions change frequently, making it difficult to collect a large amount of data or test results. Typically, marine research on such a scale is conducted with only a small number of samples (ranging from one to a dozen).

The purpose of the experiment was to verify the changes in the radar image and the level of SART signal detection due to distance, radar settings, and possibly the presence of the radar reflector. All the objectives of the study were achieved. The study, conducted using a real-world experimental method under the adopted conditions, successfully met these objectives. The qualitative evaluation of the radar image reflected the natural use of the radar function, just as it would be used in daily operations. The evaluation scales adopted by the authors allowed for the precise identification of the observed changes.

The number of trials performed also enabled a quantitative evaluation. The determined performance indicators clearly showed that the SART device is relatively reliable. At greater distances, the radar indicates the bearing and distance to the object, allowing for a precise approach. However, difficulties arise when finalizing the location of the object once the ship is close. Due to the technical limitations of the SART, which result in errors in determining its position, and the unreadability of the radar image in the vicinity of the device, it may not be possible to accurately approach the survivor. In such cases, it becomes necessary to initiate the search planning procedure and implement it. A prolonged search operation reduces the chances of saving the lives of survivors, as the greatest danger to humans in the water is hypothermia. Additionally, a survivor who has sustained injuries cannot wait long for assistance to be provided.

Research by other authors, presented in [22], also highlights the problem of detecting the SART device and selecting appropriate radar settings. In their experiment, the device was tested at different heights and orientations. A test with various radar gain and clutter settings was also performed. The results of the study indicate that an incorrect range setting led to the non-detection of the SART device, and the choice of tuning had a significant impact on the radar image and the amount of interference.

This type of real-world research is conducted relatively rarely. Therefore, its results are valuable. In order to improve maritime safety and protect human life, such studies should be carried out on a larger scale. This would make it possible to establish standardization.

5. Conclusions

In summary of the research conducted, it should be noted that the experimental method applies to specific conditions. These conditions include environmental factors (weather), types of devices used, antenna heights of both devices, distance ranges, and radar settings. In general, the results of the experiment should be interpreted as follows:

- With the radar antenna placed at a height of 6 m and the SART device at a height of 1.5 m, using the correct manual radar settings, the SART device was detected.
- The auto settings did not reduce detection under the same conditions.
- Weather conditions during the experiment were mild and did not require significant manual adjustment of the radar image due to interference from waves or rain. It is assumed that the automatic function also adjusted the tuning parameters in a similar way.
- The use of a radar reflector did not affect the SART device’s response signal.

- The detected response signal is represented as a set of wider dots, which remain visible until the transition to concentric circles.
- Acquiring an echo for tracking should be done as soon as possible. In close proximity to the SART device, it may not be possible to distinguish the echo from the background.
- The experiment was conducted using a specific radar model and SART device, which may impact the results.

The experiment conducted did not show any relationship between the automatic radar settings and the detectability of the SART device. However, such situations may still arise under different conditions, as presented in [8,22]. The problems identified regarding interference and the ability to track an object at short distances highlight the need to address these issues during seafarer training. Knowledge of the principles of search operations is therefore essential. This is especially important in fog when it is visually impossible to locate the survivor.

Conducting search operations at sea is a challenging task. Detecting and locating an object is crucial for providing assistance. Survivors should utilize support equipment, as it offers numerous advantages. Non-rescue vessels can participate and are required to follow proper procedures. When using radar, it is advisable not to select automatic settings during search operations. During normal navigation, the radar should always be properly tuned to detect unexpected distress signals. Navigators should be aware of the technical limitations of the equipment and be thoroughly familiar with radar operations and search and rescue procedures. Persons in the water should hold the SART with the antenna pointing upwards (overhead if possible), while survivors in a liferaft or lifeboat should mount it as high as possible. The height of the antenna significantly impacts the detection range.

The SART unit's response signal is activated by any of the ship's X-band radars within range. The device remains in stand-by mode for up to 96 h. The crew should therefore turn off their own radar operating in this band before evacuating the vessel and before switching on the SART device. Once the response signal is activated on the SART device, the battery will only allow the device to operate for 8 h. If there are no other vessels in the vicinity, survivors may not be detected. It is not recommended to place the SART device and the radar reflector on the same survival craft, as there is a risk of interference with the reception of the response signal.

The results obtained have scientific applications for further analysis and testing of the SART device under different conditions. They provide a reference point and expand the database. The following subjects should be examined:

- Severe weather conditions, such as rain and rough seas, require higher radar tuning; as recently reported, they could be a factor limiting the reception of the SART response signal.
- Presence of the radar reflector.
- Blanketing effects of the survival craft.
- Influence of the ship's rolling.
- Effect of wetting of the raft canopy material on signal strength loss.
- Performance of circular polarization SARTs.
- Use of other radar and SART model devices.

All research aims to improve the effectiveness of SAR operations, as the findings are also valuable for educational purposes. Proper training of seafarers ensures better performance in emergency situations. Improving the competence and knowledge of officers eliminates possible mistakes, increasing the chances of saving people at risk. More emphasis should be placed on understanding the operation of rain clutter, sea clutter, and gain, as well as the impact of automatic functions on the radar image. Crews also need to be thoroughly familiar with the use of lifesaving appliances to maximize their effectiveness and increase their chances of distress.

Similar studies should be conducted, as the results of such research impact the ability to respond quickly in dangerous situations and provide assistance to people in distress at sea.

Author Contributions: Conceptualization, M.M., M.W. and B.R.; methodology, M.W. and M.M.; software, M.W.; validation, M.M. and M.W.; formal analysis, M.W. and M.M.; investigation, M.M. and B.R.; resources, M.M. and B.R.; data curation, M.W.; writing—original draft preparation, M.M. and M.W.; writing—review and editing, M.M. and M.W.; visualization, M.M., M.W. and B.R.; supervision, M.W. and M.M.; project administration, M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research outcome has been achieved under the research project 1/S/WIiT/RD/25, financed from a subsidy of the Ministry of Science and Higher Education for statutory activities of the Maritime University of Szczecin.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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