

Article

Analysis and Prospects of an Antarctic Krill Detection Experiment Using Drifting Sonar Buoy

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Abstract: To reduce costs associated with the detection and population assessment of Antarctic krill and diversify the single detection approach, our team designed and deployed a drifting sonar buoy for krill detection in the waters surrounding Antarctica. The experimental results indicate that the drifting sonar buoy fulfills its primary functions and meets the requirements for krill detection in designated marine areas. The initial experiment lasted seven days, during which the buoy collected 157 records of speed and location data as well as 82 records of sea surface temperature and acoustic data, demonstrating its potential for krill detection. The experiment also revealed shortcomings in the initial design of the drifting sonar buoy, leading to proposed improvements. The paper further compares the advantages and disadvantages of the drifting sonar buoy and traditional fishing vessels in krill detection with the buoy offering unique benefits in low-cost deployment, labor savings, broad monitoring range, and continuous real-time data monitoring. The drifting sonar buoy serves as an excellent complement to fishing vessels in krill detection.

Keywords: Antarctic krill; drifting sonar buoy; low-cost deployment; krill detection



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1. Introduction

Antarctic krill is the most abundant marine organism around Antarctica: the total biomass of Antarctic krill is about 300–500 million tons per year [1], and it has significant nutritional and economic value [2–5]. The annual harvest of Antarctic krill is less than 1% of its total, so nations are now focusing on enhancing krill production and usage rates [4,6], striving to exploit this resource sustainably without harming the ecological balance or depleting krill stocks. To fully leverage Antarctic krill resources, it is essential to extend beyond merely boosting catch volumes; this entails conducting comprehensive research to understand krill population dynamics and total resources alongside implementing robust resource management and monitoring strategies [7–9]. These should include setting reasonable catch limits and seasonal fishing moratoriums to ensure the krill's sustainable and healthy development [10,11]. As the krill industry has evolved over decades, with current global catches totaling around 400,000 tons annually [6], collaborative international research and sustainable management practices are crucial for preserving the krill ecosystem and promoting its sustainable use despite the high costs associated with Antarctic research [5,11].

Currently, the assessment of Antarctic krill resources primarily utilizes survey vessels, which predict krill biomass using sonar equipment or fishing data onboard [12,13]. Many scholars have predicted the biomass of Antarctic krill using acoustic or fishing data with considerable success. However, surveys conducted by vessels are labor-intensive and

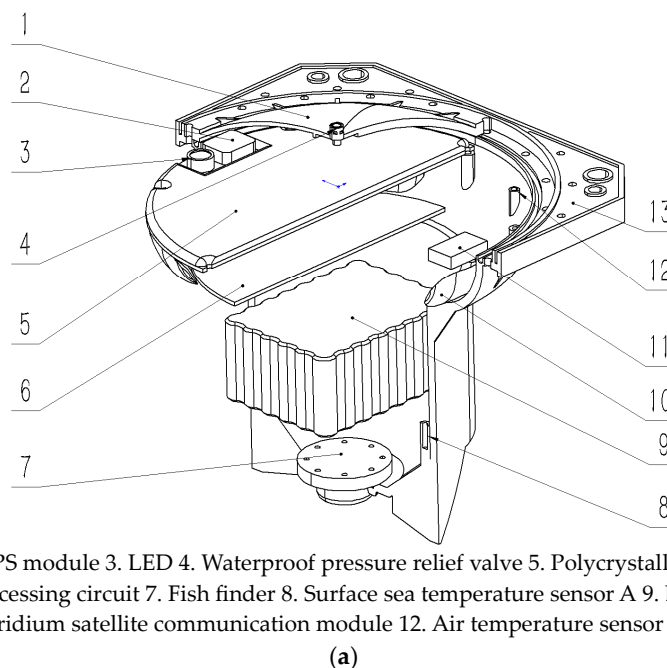
costly, and given that krill are distributed in the remote and harsh maritime regions of Antarctica, prolonged survey operations become even more challenging [4]. Sonar, as a common method for marine detection, has been widely applied in recent years. PAM (Passive Acoustic Monitoring) is used to detect marine mammals [14,15], enhancing our understanding and protection of marine cetaceans. Active sonar technology is often used in resource assessment [12,13,16–19] and marine mapping [20], playing a significant role in these areas. At the same time, sonar technology has been increasingly refined and integrated with emerging technologies like artificial intelligence, allowing it to better serve current production and research work. Buoys, as monitoring and navigational tools at sea, offer the advantages of low cost and flexible deployment [21,22], and they are currently widely used in fields such as marine research [23–26], navigational safety [27–29], meteorological monitoring [30–33], and fishery [34–36].

Therefore, our team proposes the use of small sonar buoys for the assessment of Antarctic krill resources and has conducted preliminary experiments. Utilizing this method for the assessment of Antarctic krill resources is cost-effective, and detection is sustainable. It can serve as an excellent supplement to research vessels for assessing krill resources, reducing the workload of survey vessels. Additionally, since sonar buoys can perform acoustic monitoring over extended periods in designated maritime areas, they help enhance the accuracy of krill resource assessments. This approach offers new insights for the conservation and evaluation of Antarctic krill resources. The preliminary experiments on krill detection have achieved the expected objectives, providing evidence of using drifting sonar buoys to detect Antarctic krill while also identifying some deficiencies. The experimental results and analysis will be detailed in this paper.

2. Materials and Methods

2.1. Buoy Design

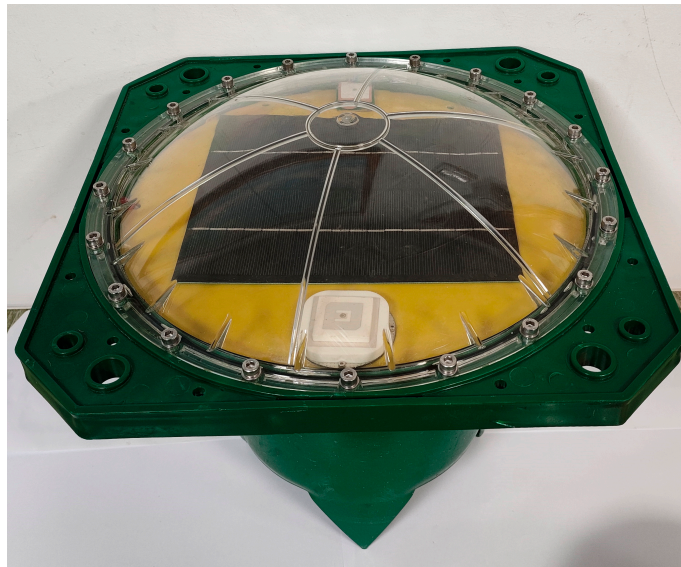
The experimental buoy used in this study has dimensions of $350 \times 350 \times 350$ mm and weighs approximately 8 kg. It is equipped with two temperature sensors and a small fish finder. The buoy is powered by batteries, and the batteries are charged by a solar panel. Additionally, the buoy is equipped with satellite communication capability, allowing the detected data to be transmitted back through the satellite system. The specific structure of the buoy is depicted in Figure 1.



1. Cover 2. GPS module 3. LED 4. Waterproof pressure relief valve 5. Polycrystalline silicon solar module 6. Processing circuit 7. Fish finder 8. Surface sea temperature sensor A 9. Battery 10. Silica gel 11. Iridium satellite communication module 12. Air temperature sensor B 13. Hull

(a)

Figure 1. Cont.



(b)

Figure 1. Buoy. (a) Buoy design. (b) Photo of the buoy.

The external structure of the buoy consists of a waterproof casing. The fish finder is located in the center of the bottom and can emit sound signals at frequencies of 83 kHz or 200 kHz. It can detect depths ranging from 1 to 250 m and is adjustable. On one side of the bottom of the buoy, there is a temperature sensor used to measure the temperature of the seawater. Above the fish finder is a battery that powers the entire buoy. Additionally, there is another temperature sensor above the battery. A GPS module on the top is used for positioning, and a satellite communication module can transmit all data including time, latitude, longitude, heading, speed, air temperature, sea surface temperature, and echo data. The layout of the entire buoy is compact, the structure is simple, and the functions of each module are clear and independent, allowing the buoy to successfully complete data collection tasks for each module. The buoy collects data every two hours during normal operation or can be activated and data can be collected through software on a computer. The specific process is shown in Figure 2.

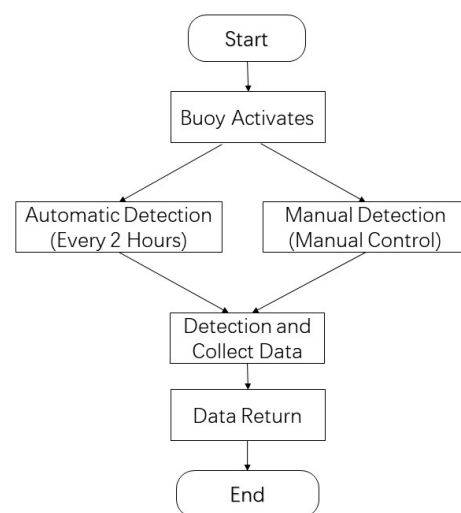


Figure 2. The workflow diagram of the buoy.

The materials used for the entire buoy casing are renewable, and injection molding technology is utilized. Injection molding is the most common and widely applied method in plastic processing. The method involves injecting molten plastic into a mold, which

cools and solidifies to form the desired casing shape. Parts produced using injection molding technology have high efficiency and accuracy, making them suitable for large-scale production. The overall fabrication technology of this buoy is mature and low-cost. Therefore, it meets the requirements for the large-scale deployment of Antarctic krill detection.

2.2. Experiments

On 23 January 2023, at 16:11, the buoy was deployed by the Antarctic krill vessel “Shen Lan” at coordinates 46.1322° W, 60.036498° S. The buoy operated normally until 30 January 2023, at 18:39, at which point it was located at coordinates 45.6795° W, 60.70572° S. The buoy maintained normal operation for a duration of seven days, and its movement trajectory is shown in Figure 3. The buoy moved from east to 46.53° W, west to 45.68° W, south to 60.73° S, and north to 60.68° S. The spatial movement of the buoy was relatively small. During this period, a total of 157 sets of data were transmitted back via satellite, including ambient temperature (Figure 4), speed, and location information in 157 sets, as well as sonar data and sea surface temperature (Figure 5) in 82 sets.

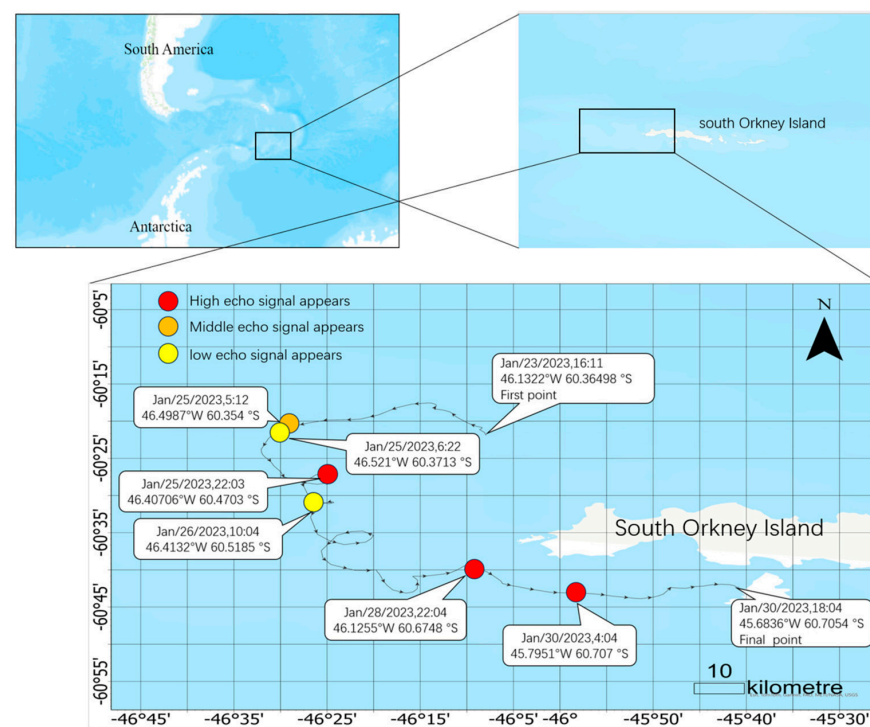


Figure 3. Krill distribution.

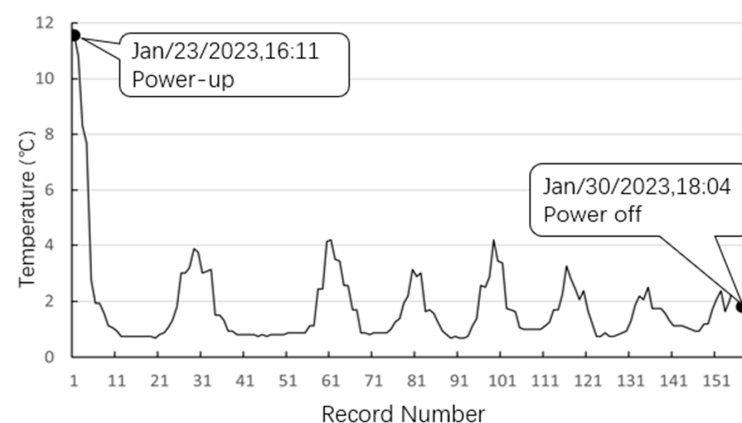


Figure 4. Line chart of ambient air temperature.

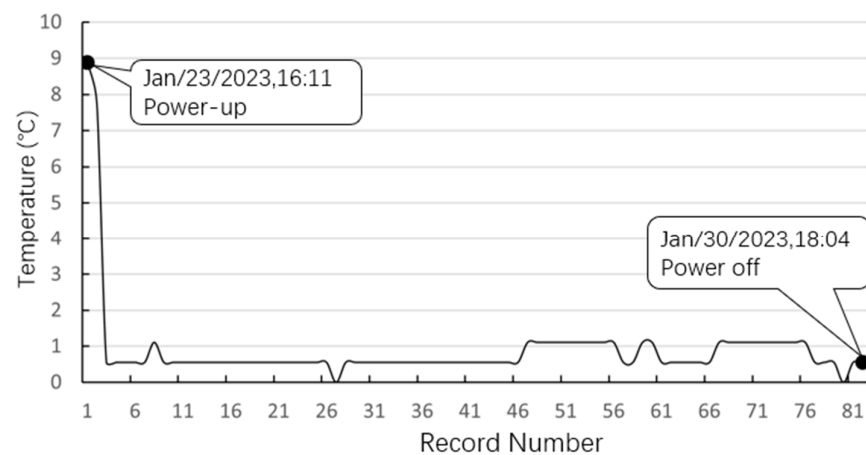


Figure 5. Line chart of sea surface temperature.

When the buoy was powered on, it was initially on the ship before being placed into the sea. Consequently, the temperature readings collected at the first two points were higher. Figures 4 and 5 illustrate that the ambient temperature fluctuates within a range of two degrees. Additionally, the sea surface temperature remains relatively low, mostly below one degree, with minor fluctuations.

2.3. Signal Analysis

In the collected echo signals, we consider echoes with stronger signals to indicate the presence of krill, and for echoes with weaker signals, we assume that krill are not present at that point. Figure 6 presents line charts of the echo signal intensity for six sets of data. All six sets of data are real echo data collected from experiments. Three sets are considered to contain krill, and three sets are considered not to contain krill.

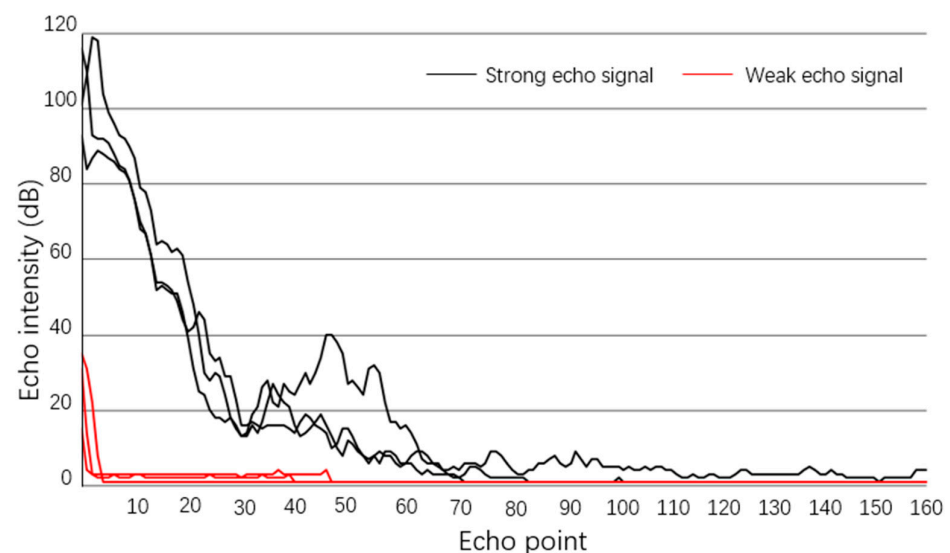


Figure 6. Echo intensity comparison chart.

In the figure, it can be seen that there is a significant difference in the echo signal intensities between the two types. It is clearly discernible whether a strong echo signal is present. In the experiment, the sonar detection depth on the buoy is 250 m, which basically covers the activity depth of Antarctic krill. In the detection area, a total of 160 sets of echo

intensity signals were returned. For any detection, the depth corresponding to the n -th echo point is given by (Equation (1)):

$$d_n = \frac{250}{160}n \quad (1)$$

2.4. Results Validation

The Simrad EK80 (Kongsberg, Horten, Norway) is a high-precision scientific echosounder and ADCP system designed to monitor underwater ecosystems. Simrad EK80 is capable of adjusting to six frequencies: 18 kHz, 38 kHz, 70 kHz, 120 kHz, 200 kHz, and 333 kHz. It can accurately detect various water layers and different krill, making it a common instrument for underwater resource detection [37]. In order to verify the accuracy of the buoy-collected signals and the correctness of krill identification, we utilized the Simrad EK80 scientific echosounder system installed on the “Deep Blue” vessel for krill resource detection during buoy signal collection. By comparing the data from the scientific echosounder with the buoy-collected data, we validated the krill detection effectiveness of the small sonar buoys.

Figure 7a shows the sonar image after the buoy was deployed, indicating the absence of krill in the area. Figure 7b depicts the detection of krill by our vessel near the buoy around 10 a.m. on 25 January 2023, confirming the findings from the buoy’s sonar. Our team conducted a thorough analysis of multiple locations, revealing a correlation between the echo data of krill in Figure 6 and the sonar images in Figure 7. Specifically, when Figure 6 showed a low echo signal, Figure 7a displayed no significant krill groups near the buoy. Conversely, a strong echo signal in Figure 6 corresponded to significant krill groups in the sonar images, as seen in Figure 7b. This comparison demonstrates the drifting sonar buoy’s ability to provide clear and strong echo signals during krill detection. The echo intensity exhibits a gradual decrease, remaining low when there are no krill groups nearby. These results underscore the drifting sonar buoy’s accuracy in detecting Antarctic krill groups.

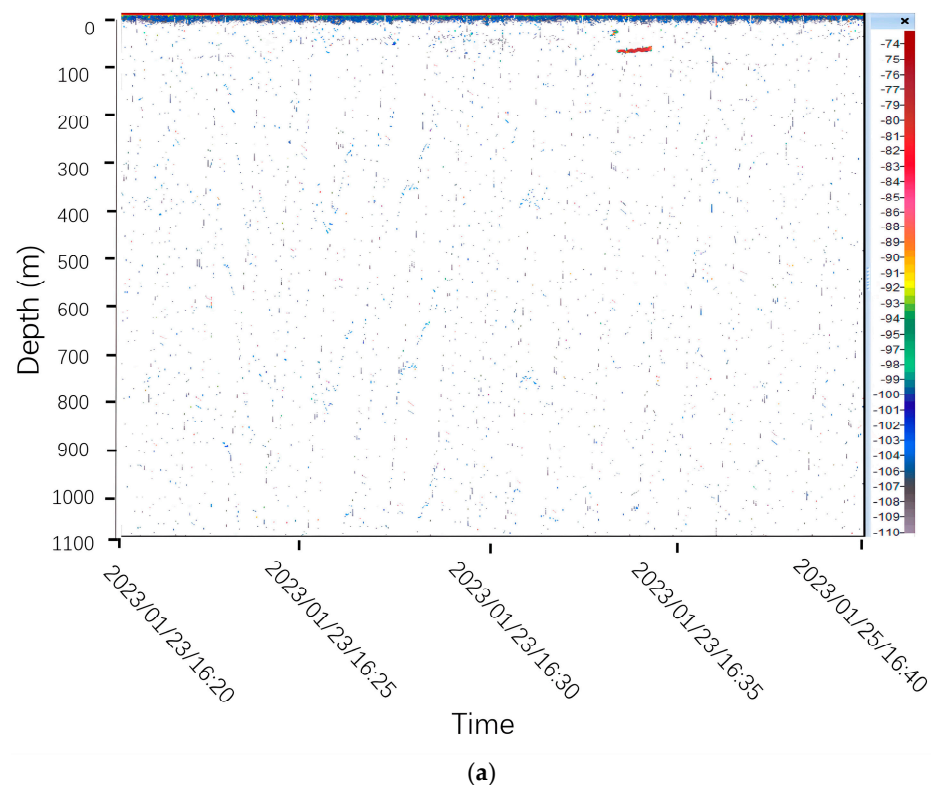


Figure 7. Cont.

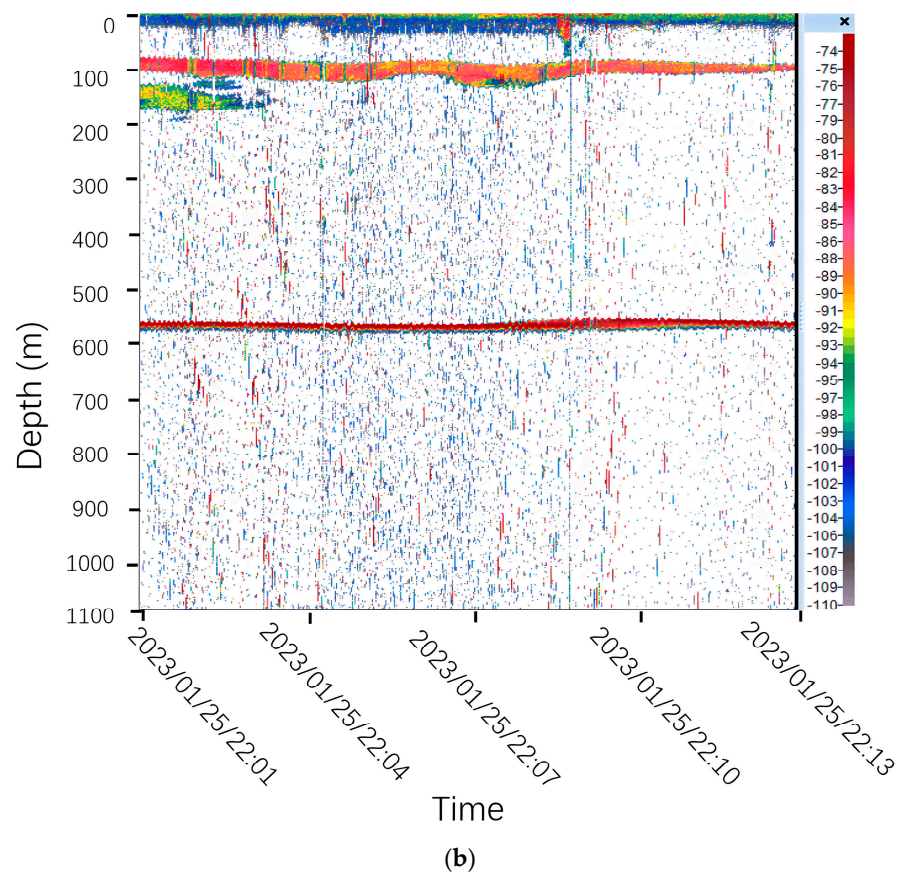


Figure 7. Target intensity (dB) echogram. (a) No Antarctic krill. (b) Antarctic krill.

3. Results

3.1. Data Collection Results

The buoy operated for seven days. As shown in Figure 3, the buoy moved randomly within a relatively small area. The collected data included crucial indicators for fishery prediction, such as water temperature, current speed, and location. In addition, among the 82 sets of sonar data collected, six sets contained strong echo signals (as depicted in Figure 3), which suggests the presence of Antarctic krill swarms at those locations. We divided these six strong echo signals into three levels based on signal strength; in the future, we will correlate the divided strength levels with krill density ranges. The collection of sonar data plays a positive role in assessing the biomass of Antarctic krill species and in guiding the establishment of fishing quotas [13,16].

3.2. Functional Test Results

This experiment tested the key performances of the buoy, providing theoretical support for the use of drifting sonar buoys in Antarctic krill detection. The experiments successfully validated the buoy's waterproofing, stability, and corrosion resistance, which are essential for all operations. They confirmed that sonar devices, temperature sensors, flow sensors, and solar panels function properly in complex maritime conditions. The experiments also verified that the buoy collects data as intended; this point has been discussed previously in Section 2.1. It is worth noting that our setting of the sampling interval is based on considerations of energy consumption and the efficiency of solar power generation [38]. The buoy's data collection logic, established based on preliminary assessments, efficiently reduces energy consumption by scheduling data acquisition at set intervals, allowing the buoy to operate effectively over extended periods. Additionally, the buoy's satellite communication capabilities were validated, with data successfully transmitted from the Antarctic to the base station, which also issued multiple commands for data collection.

4. Discussion

4.1. Experimental Findings and Improvements

While the experiments successfully demonstrated the buoy’s basic functionalities, they also revealed several issues. First, the low sunlight intensity in the Antarctic leads to suboptimal solar panel efficiency, potentially resulting in power deficits during extended operations. Second, the placement of buoys should be slightly far from the island to avoid stranding on islands. Finally, environmentally friendly, non-polluting materials should be used before deploying buoys on a large scale to prevent them from becoming marine debris and causing pollution.

Our team has proposed buoy design improvements to address these issues. Firstly, these include replacing current batteries with lithium batteries to achieve higher energy density and longer operational times [39] and adding a smaller backup battery that activates to send only positional data when the primary battery fails, facilitating buoy recovery. At the same time, we will attempt to utilize wave energy as a power source for buoys [40,41]. Secondly, a double-layer hull design is recommended: an inner layer of acrylonitrile butadiene styrene (ABS) for strength and an outer layer of acrylic (PMMA) for corrosion resistance [42,43], enhancing the buoy’s durability and ability to withstand harsh marine conditions. Thirdly, the placement location for subsequent attachments should be selected slightly further from the island to prevent the buoy from running aground.

4.2. Analysis of the Advantages and Disadvantages of Buoys

Our team use drifting sonar buoy detection of Antarctic krill, which is a new attempt. The experimental results indicate that the buoys have potential for Antarctic krill detection, offering a new solution for the analysis and assessment of krill stock and species. Compared to using research vessels for marine resource detection [4,44], sonar buoys have the following advantages and disadvantages outlined in Table 1 [45,46].

Table 1. Comparison of the advantages and disadvantages of buoys and exploration ship.

	Buoy	Exploration Ship
pros	Low cost Saves manpower Wide coverage Continuous monitoring Real-time monitoring	Advanced detection equipment Defined detection area High detection accuracy Wide range of activity exploratory fishing
cons	Limited data accuracy High data transmission cost Limited depth coverage Possible ecological disturbance Random detection locations	High cost Consumes manpower Affects ecological balance Affected by bad weather Restrictions due to regulations and policies

Below, the advantages and disadvantages of floating buoys are detailed.
The advantages of using buoy detection are outlined below:

- Low cost: The design of krill buoys is compact and simple; the manufacturing cost of a single buoy is only around USD 300, which is extremely low compared to the several hundred thousand dollars required for a single voyage of a survey vessel. This makes the manufacturing and maintenance costs of buoys very economical.
- Saves manpower: Compared to survey vessels which require crews of dozens who spend extended periods at sea, sonobuoys demand far fewer personnel. Most buoys can be deployed or retrieved alongside research ships or local fishing vessels when they reach specific locations. Sonobuoys are small and easy to transport. Even if specialized ships are needed for their deployment and retrieval, there are no stringent requirements regarding the size of the ships or the number of crew members.

- **Wide coverage:** In krill detection, sonar buoys rely on multiple units working in concert across various marine regions. Due to their small size, low cost, and strong environmental adaptability, they can be deployed extensively. Essentially, any area accessible by ships can be covered by sonar buoy detection.
- **Continuous monitoring:** Another significant advantage of sonar buoys is continuous monitoring. Unlike survey vessels, which require resupply and crew rest and thus cannot operate year-round, sonar buoys leverage the traditional buoy's benefits. They are stable, durable, and capable of enduring sea conditions to provide uninterrupted data collection.
- **Real-time monitoring:** Real-time monitoring is another advantage of sonar buoys. Thanks to PC software design, users can control the buoy's dynamics in real time and issue data collection commands, allowing for on-demand, real-time detection as per the user's requirements.

The disadvantages of using buoy detection are outlined below.

- **Limited data accuracy:** Compared to the large equipment on survey vessels, sonar buoys inevitably have reduced data collection precision, which may not meet the requirements for high-precision detection. However, as sonar technology advances and devices become more compact, higher precision sonar equipment may also be used in sonar buoys in the future.
- **High data transmission cost:** Traditional krill detection methods involve the physical storage of data, whereas sonar buoys transmit data via satellite, making data acquisition more costly compared to traditional methods. Therefore, it is necessary to control the frequency of detection and the amount of data transmitted to reduce transmission costs.
- **Limited depth coverage:** The sonar currently tested has a maximum detection depth of 150 m, which generally meets the requirements for Antarctic krill detection depth.
- **However, research vessels can explore deeper waters and perform multiple detection tasks including other species than the krill; in comparison, the depth of buoy detection is limited, which may pose certain restrictions when detecting other deeper species.**
- **Possible ecological disturbance:** Sonar buoys may encounter various extreme conditions on complex sea surfaces, resulting in damage and debris becoming marine litter. The team will next use biodegradable materials to reduce potential environmental impacts. Additionally, the acoustic signals emitted by active sonar may affect marine life, but for drifting sonar buoys, however, the primary species in the deployment area and the species that need protection can be considered in advance. By selecting the appropriate signal frequency, the impact of sonar sounds on the species in the deployment area can be reduced or even eliminated.
- **Random detection locations:** Random detection locations refer to the erratic movements of buoys within a certain area as they drift with ocean currents during krill detection. The positions of the buoys are uncertain within a specific region, preventing them from reaching precise designated locations for detection.

In summary, buoys have both advantages and disadvantages compared to survey vessels in krill detection. Relying solely on survey vessels in the vast Antarctic seas is insufficient; multiple detection methods are needed for a more accurate assessment of krill populations and their characteristics [47]. Thus, sonar buoys can supplement vessel-based detection. Although the current sonar buoy technology for Antarctic krill detection is not yet mature and lacks a systematic approach, it is foreseeable that with the ongoing development of sonar buoys in this area, the future will see reduced manufacturing costs, improved data quality, more rational deployment locations, and closer data connections between buoys.

5. Conclusions

This study explored the feasibility and effectiveness of drifting sonar buoys for assessing and monitoring Antarctic krill resources through preliminary experiments by deploying a buoy in the Antarctic waters to test their operational functionality at sea. The study indicates that our drifting sonar buoy successfully completed initial tasks, demonstrating unique advantages such as low-cost deployment, conservation of human resources, extensive monitoring coverage, and the capability for continuous and real-time data monitoring. However, the sonar buoy system also presents certain limitations and challenges, such as lower data collection precision compared to large survey vessels and high data transmission costs [38]. Facing these challenges, future research needs to further optimize buoy design to enhance its stability and data collection capabilities in extreme marine environments [48,49].

The limitations of the study include a small amount of preliminary experimental data, a single data source, and a lack of more in-depth data analysis. Our team will improve the buoys according to the measures proposed in this paper and use the improved buoys to expand the scale and duration of experiments, further advancing the application of sonar buoys in the assessment of Antarctic krill species.

In summary, the sonar buoy has the aforementioned series of advantages in detecting krill. Despite some technical and operational challenges, with technological advancements and accumulating experience, sonar buoys are expected to become a vital tool in the assessment and management of Antarctic krill resources, significantly supporting global marine ecological research and resource management.

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Data Availability Statement: The data collected by the buoy can be found at the following link: https://drive.google.com/file/d/1XN1-qAJCOFPA-zqGih_YD2gUmOKaUbT0/view?usp=drive_link (accessed on 10 June 2024).

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