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Review

Underwater Acoustic Technology-Based Monitoring of Oil Spill: A Review

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Abstract: Acoustic monitoring is an efficient technique for oil spill detection, and the development of acoustic technology is conducive to achieving real-time monitoring of underwater oil spills, providing data references and guidance for emergency response work. Starting from the research background of oil spills, this review summarizes and evaluates the existing research on acoustic technology for monitoring underwater oil spills. Underwater oil spills are more complex than surface oil spills, and further research is needed to investigate the feasibility of acoustic technology in underwater oil spill monitoring, verify the accuracy of monitoring data, and assess its value. In the future, the impact mechanism and dynamic research of acoustic technology in oil spill monitoring should be explored, and the advantages and differences between acoustic technology and other detection techniques should be compared. The significance of auxiliary mechanisms combined with acoustic technology in oil spill monitoring should be studied. Moreover, acoustic research methods and experimental techniques should be enriched and improved to fully tap into the future value of acoustic technology.

Keywords: acoustic technology; underwater oil spill; oil spill monitoring; sunken oil

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1. Introduction

With the increasing energy consumption worldwide, offshore oil exploration and development activities have gradually intensified, and the focus of exploration and development is shifting from shallow water to deep sea, which has led to an increase in oil spill accidents. Figure 1 summarizes the causes of marine oil spill incidents of 50 t and above in China from 1974–2018 [1]. Oil spill accidents not only cause huge economic losses, but also seriously damage the ecosystem. Petroleum extraction, transportation, and natural seepage are the main sources of oil release. While the extraction and transportation process, mainly oil pipeline failures, tanker collisions and subsea well blowouts cause oil spills to occur [2–4]. After an underwater oil spill occurs, methane gas and oil are released from the damaged wellhead. Only a small portion of the oil rises to the surface to form an oil slick, while most of the oil exists in the water column in the form of oil droplets and mixtures. There is a significant difference between the amount of oil leaving the wellhead and the amount of oil reaching the sea surface, and providing a monitoring feedback mechanism is crucial as a guide for responding to the spill in the short term [5–7]. This feedback mechanism can be used to guide subsequent oil spill response work. Therefore, emergency monitoring of oil spills has become a major issue that needs to be addressed urgently in the offshore oil industry.

Currently, the emergency response measures for oil spills are relatively mature, but oil spill incidents still exist due to insufficient oil spill monitoring work [8,9]. Marine oil spills include surface oil spills and underwater oil spills. Monitoring technology for surface oil spills is relatively mature, with breakthroughs in optical sensor monitoring, synthetic aperture radar (SAR) image monitoring, and ocean buoy remote sensing [10–12].

Compared to surface oil spills, underwater oil spills are more complex, with characteristics such as large leak volume, long duration, and uncontrollability. However, the energy of radio wave or light wave is easily absorbed by seawater and is not suitable for long-distance transmission in the ocean, making it difficult to grasp the situation of underwater oil spills. Compared with traditional surface oil spill monitoring technology, sound wave is stable in propagating through seawater and have greater application value. Therefore, acoustic technology is a more suitable method for realizing real-time underwater oil spill monitoring.

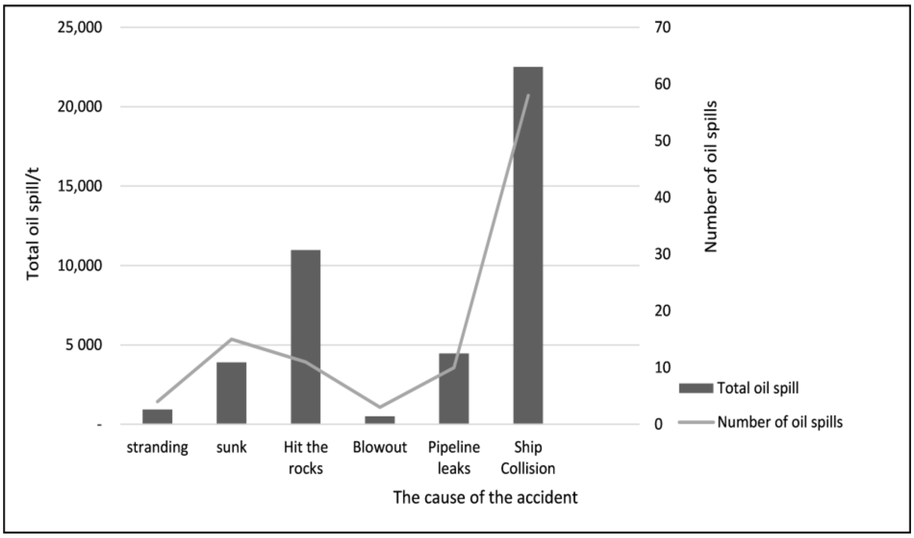

Figure 1. Causes of marine oil spill accidents of 50 tons and above in China, 1974–2018 statistics.

Acoustic oil spill monitoring technology mainly relies on acoustic detection equipment, including multibeam sonar sensors, acoustic doppler current profilers, and so on [13]. Oil and gas belong to different media from seawater. When the sound wave propagates to the interface between different media, reflection and scattering phenomena occur. By analyzing the reflected sound wave, information such as the spreading speed of the underwater oil spill, the thickness of the oil layer, and oil spill volume can be obtained.

This article provides an overview of research progress in using acoustic technology to detect oil spills, discussing the background of underwater oil spills, the development of acoustics, feasibility analysis, and future prospects from different perspectives. It also addresses key issues related to using acoustic technology to monitor underwater oil spills. It is important to note that the four aspects mentioned above have internal connections and logical relationships, mainly reflected in: First, the background of oil spills as the scenario for the application of acoustic technology is a crucial premise and key to solving the problem of oil spill monitoring. Second, the application mechanism of acoustic technology in various aspects can provide research ideas for monitoring underwater oil spills. Third, the application effect of acoustic technology in oil spills can provide a new perspective for the future development of acoustic technology.

2. Marine oil Spill Investigations

2.1. Analysis of Marine Oil Spill Movement

Understanding the movement of oil droplets in water is an important factor in the study of monitoring technology. Through the research, it is found that the oil spill behavior and fate of subsea oil spill in the rising process are obviously different from that of surface oil spill due to the influence of tide, temperature, and pressure. The behavior of underwater oil spill mainly includes oil and gas particle size distribution, ascent velocity, oil and gas separation, and reel suction, which will eventually exist in the hydrate or dissolve in the water column, or exist in the suspended plume. There have been a large number of experimental and simulated studies on underwater oil spills, such as the real distribution of oil droplets released from the seabed, the uncertainty of the size distribution of oil droplets affecting the short-term fate of deep-sea oil, and the horizontal wave and spiral upward movement of rising oil droplets [6,14,15]. Most oil droplets float under the combined effect of initial momentum and buoyancy, and those that rise to the sea surface form an oil film that is influenced by both ocean currents and wind, allowing it to travel further and diffuse over a larger area. Oil droplets of different sizes undergo horizontal diffusion in water, with larger ones floating to the sea surface and expanding into an oil film due to the influence of gravity, while smaller ones remain suspended in the water [16]. In the nearshore environment, oil spills can interact with suspended sediment, forming oil sediment residues [17–19]. Figure 2 shows a conceptual model of the various oil residues found in the nearshore environment, where oil interacts primarily with coarse sediments to form sediment–oil agglomerates; and large oil slicks can also interact with sediments to produce sediment–oil mats, which float after long-term weathering to a black or brown ball of oil of varying shapes that floats in nearshore waters. Oil spill monitoring requires advance knowledge of the dispersal behavior of spilled oil and the formation of conjunctures with other materials. A conceptual model of nearshore oil residues can provide a reference aid for the implementation and deployment of oil spill monitoring. Previous studies have summarized the characteristics of ocean oil spills from the conditions, effects, and processes of oil and gas diffusion, which can help subsequent studies to accurately grasp the evolutionary pattern of oil spills and provide reference guidance for acoustic monitoring.

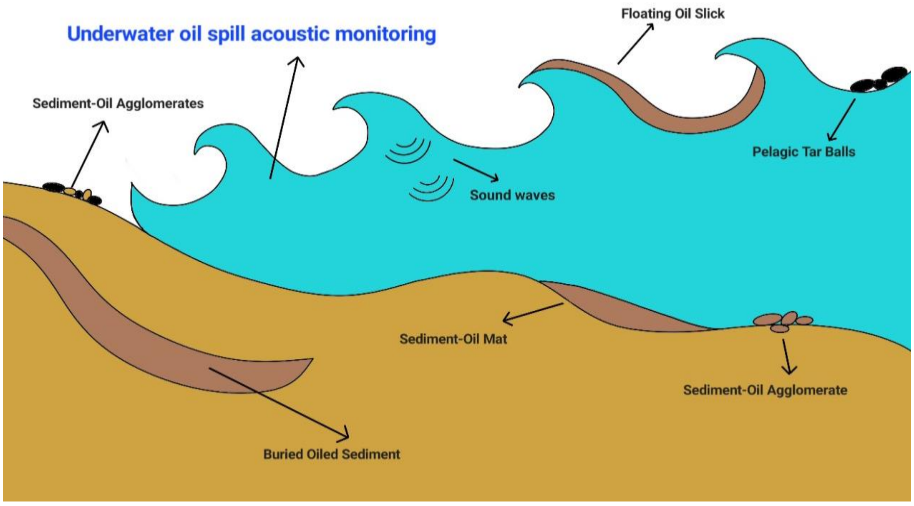

Figure 2. Conceptual model of various oil residues found in nearshore environments.

2.2. Limitations of Underwater Oil Spill Monitoring

Different monitoring methods are needed for underwater and surface oil spill situations. Optical and electromagnetic technologies are more suitable for solving oil spills on the water surface [20,21], and further research is currently being carried out. However, underwater oil spills occur in a high-pressure and low-temperature environment, with a relatively complex movement process that can generate effects such as entrainment, and oil and gas dissolution [22,23]. In addition, the distribution and rising speed of oil and gas will change, and the state of oil and gas is unstable [24,25]. As the oil spill occurs in the underwater environment, the energy produced by optical and electromagnetic technologies is greatly absorbed by seawater, making it difficult to achieve energy emission and reception, and general equipment cannot meet the requirements. Furthermore, human monitoring poses significant risks. It can be concluded that monitoring for underwater oil spills is highly limited due to complex conditions and high monitoring equipment requirements.

3. Research on Underwater Oil Spill Monitoring Technology

3.1. Traditional Oil Spill Monitoring Method

Traditional methods for monitoring marine oil spills include optical and remote sensing technologies. Currently, optical technologies have been used to monitor oil spills using thermal infrared images, ultraviolet spectroscopy, and fluorescence spectroscopy [20,26–30]. Optical video survey and other non-contact technology is easy to operate; however, the monitoring speed is slow and, limited by the light conditions, does not meet the requirements of emergency response. Due to the absorption and scattering of light in seawater, light transmission has a very short distance and the application range is limited by distance. Experimental techniques such as airborne laser fluorescence have been proven to detect aromatic hydrocarbons in shallow waters, but the feasibility of this technology decreases with increasing depth or seawater turbidity; in addition, it is only suitable for estimating the amount of oil that has reached the surface and cannot evaluate the internal oil spill situation in the ocean.

Remote sensing technology is usually used to detect and track oil spills on the sea surface, and synthetic aperture radar (SAR) images can be used for oil spill monitoring [21]. SAR remote sensing images have a wide coverage range and can monitor oil spills on the ocean for long periods of time. In the marine environment, remote sensing monitoring technology uses thermal scanners, laser-induced fluorescence systems, and hyperspectral imaging for monitoring [31–33]. SAR remote sensing images can be analyzed through model algorithms, including neural network models, oil drift models, genetic algorithms, machine learning algorithms, deep learning methods, etc. [34–38]. However, electromagnetic wave has a large signal attenuation coefficient when transmitting in seawater, requiring a lot of energy to support transmission. Remote-sensing technology and optical technology are only suitable for monitoring oil spills on the sea surface; in addition, they can only monitor oil or gas that has already reached the surface, and cannot directly determine the dynamic situation in the water column. They are useful for large-scale ship oil spill accidents, but are not suitable for monitoring deep-sea oil spills and often involve long time scales for detection.

Currently, there is a need for a fast, real-time, and efficient technology to scan and sample the water column to determine the physical and dynamic characteristics of oil plumes. Table 1 compares the differences between acoustic technology and optical and remote sensing technologies, and finds that acoustic technology has potential for monitoring underwater oil spills.

Table 1. Technology comparison.

Category	Depth of Investigation	Directivity	Attenuation Degree	Monitoring Range	Operability	Cost
Acoustic technology	High depth of penetration	Strong directivity	Weak attenuation	Large range	Easy operation and high flexibility	Low
Optical technology	Short distance	Weak directivity	Large attenuation	Small range	Easy operation and high flexibility	High
Remote-sensing monitoring	Short distance and suitable for sea-surface monitoring	Strong directivity	Large attenuation	Large range	Complicated and low sensitivity	High

3.2. Principles of Acoustic Technology

Acoustics is a field of wave mechanics in physics that studies mechanical waves in a medium, including sound waves, ultrasonic waves, and infrasonic waves. Acoustic technology mainly analyzes the changes and processes in sound waves through their emission and reception, in order to obtain the necessary information. Underwater acoustics primarily studies the generation, propagation, and reception of sound waves in water. A sound wave is currently the only known wave that can propagate over long distances in water [39], and its propagation performance is far better than electromagnetic waves such as light waves and radio waves [40]. This advantage highlights the value of acoustic technology in the monitoring of oil spills underwater.

3.2.1. Basic Principles of Acoustic Propagation

The basic principle of acoustic technology is to use the emission and reception of sound waves to obtain information about the target [41,42]. An acoustic transmitter continuously emits periodic small pulses, and the sound waves are backscattered upon contacting the hydrocarbons present in the water column [43]. An acoustic receiver continuously receives the echoes reflected by deep-sea oil and gas particles. By comparing the collected echoes with the pulses of the emitted sound wave, information about the state of oil and gas, and dynamic information such as rising speed can be obtained.

3.2.2. Acoustic Scattering Principle

In nature, sound waves are scattered and reflected when they encounter obstacles [44]. Figure 3 shows the process of sound waves scattering by a target object, which occurs when the sound wave is projected onto a rough interface or particles in a medium, and propagates in different directions [43,45]. The condition for scattering is that the wavelength of the sound wave is much smaller than the size of the obstacle, and small obstacles will become new sources of ultrasound and emit waves in all directions when scattered [46]. In the event of an oil spill, seawater and oil and gas form three different media, between the oil droplets and seawater, between the bubbles and seawater, and between the oil droplets and the bubbles [47–49]. When a sound wave propagates to the interface between oil droplets, seawater, and bubbles, scattering occurs. In the process of scattering, the scattered signal carries information about the oil and gas obstacles due to different mechanisms of scattering echo generation. In underwater oil spill monitoring, the scattered echo signal produced by the detection sound wave encountering an oil and gas target is used to obtain dynamic information about the spill. Acoustic backscatter signals can also be used to analyze the state information of oil and gas.

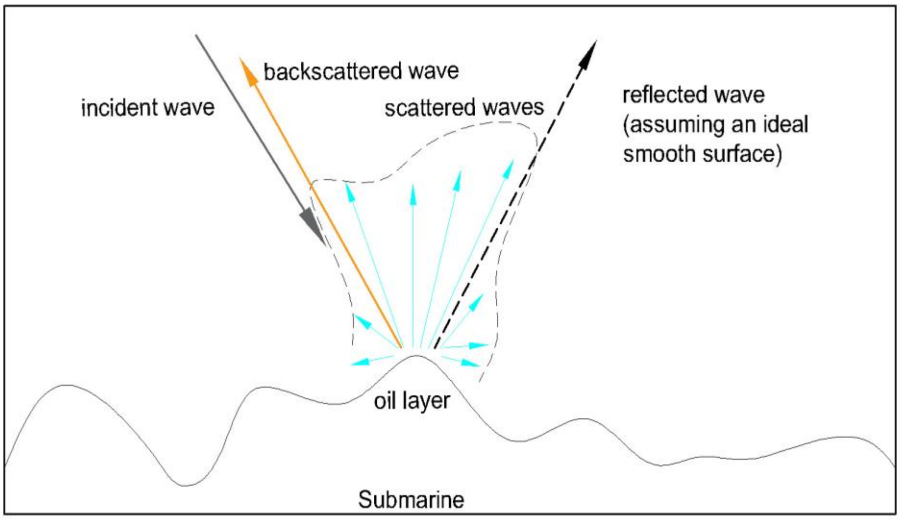

Figure 3. The principle of the acoustic wave (back) scattering phenomenon. (The black solid line represents the incident wave. the yellow solid line represents the backscattered wave. The black dashed line represents the reflected wave. The blue line in the dashed box represents the scattered wave. The blank part represents the seawater medium, and the black curve below represents the oil layer medium.).

3.2.3. Sound Wave Influence Factor

The speed of sound propagation varies with the elasticity and density of the medium. Since the density and adiabatic compressibility of seawater are greatly affected by its temperature, salinity, and pressure, the speed of sound in seawater changes continuously with these factors. Therefore, these factors need to be carefully considered in oil spill monitoring. Many researchers have found through experiments and theoretical analyses that temperature and the complex underwater environment have the greatest impact on sound velocity. Due to the sound channel phenomenon, low-frequency sound wave consumes less energy and can propagate over longer distances in the ocean. Due to the different acoustic properties of different substances and the stronger focusing effect of the sound wave as the emission source approaches the sound channel axis, the propagation speed of the sound wave is also faster, and the received information is clearer. The sound channel phenomenon and focusing effect provide reference guidance for the frequency selection of acoustic equipment used in oil spill monitoring [9]. Selecting a more suitable sound channel frequency can not only reduce sound attenuation, but also improve the efficiency of oil spill monitoring.

3.3. Advances in Acoustic Technology for Monitoring Underwater Oil Spills

After several accident scene investigations and research experiments, acoustic technology has been proven to be the best method for detecting underwater oil spills. When an oil spill occurs on the seafloor, a large amount of hydrocarbons are released and spread into the water column in the form of bubbles, dissolved gas, and oil droplets. In oil spill monitoring, it is necessary to comprehensively analyze the changes in acoustic waves when they encounter oil droplets and gas (Figure 4). The characteristics are determined based on the scattering of sound waves by the target.

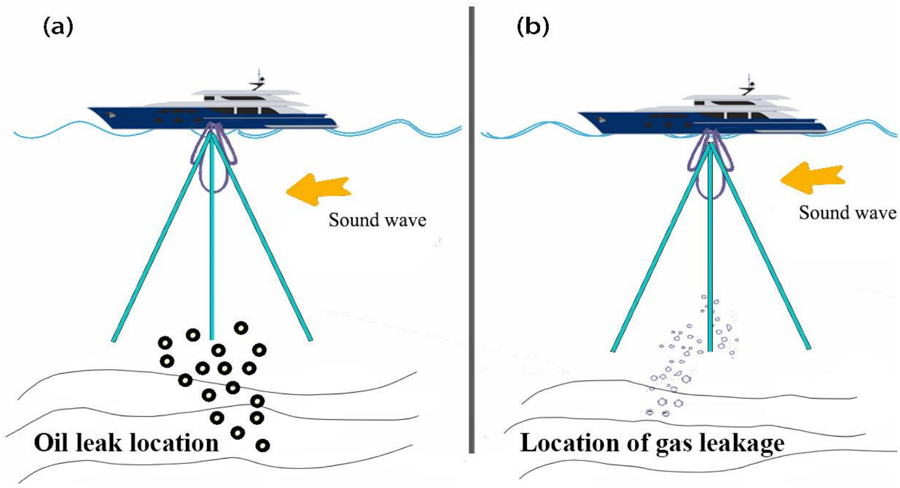

Figure 4. (**a**) Acoustic monitoring of oil droplets; (**b**) acoustic monitoring of leaking gas.

3.3.1. Progress in Acoustic Monitoring of Underwater Gas Leaks

Foreign countries have already begun to monitor methane bubbles released from the deep sea, and optical technology has been used to quantify the ocean bubble flow using wide-baseline stereo photogrammetry [50,51]. However, optical waves are greatly attenuated when propagated in seawater due to the effects of underwater turbulence and seawater turbidity. Compared to light wave, sound wave has less energy loss in seawater. In recent years, acoustic backscatter has been applied to quantitatively monitor various targets in seawater, showing the potential of acoustic technology in the detection of an oil spill. Additionally, acoustic detectors are suitable for large spatial scales and do not affect seabed organisms. Using the high acoustic impedance and strong scattering characteristics of bubbles to accurately identify and locate ocean leaks is an important breakthrough in the acoustic monitoring of oil spills. Previous studies have used echosounders (Figure 5) and side-scan sonar to monitor the methane bubble plumes from underwater leakage, predicting relative flux and the fate of bubbles by analyzing the acoustic target intensity profile [52–55]. These acoustic methods can be used to monitor natural hydrocarbon leaks and provide references for artificial oil spill monitoring. However, these acoustic methods require advance knowledge of the nature of leakage, such as the size distribution of bubbles, the relative number of bubbles in the water column, and the physical properties of the gases present in the leak. It is difficult to perform a complete acoustic inversion to estimate the natural gas flow rates, and the prediction uncertainty is high, requiring other means to properly constrain the measurements and quickly estimate the dynamic leakage reaching the surface on a large time and spatial scale.

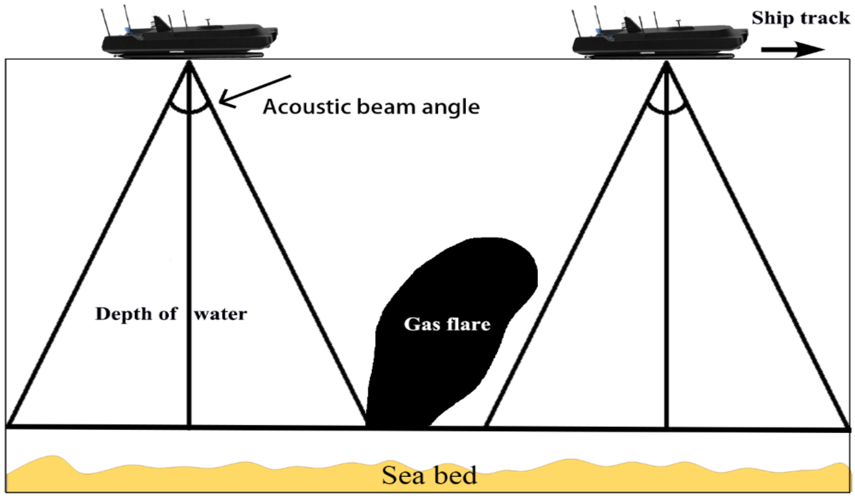

Figure 5. Acoustic bubble monitoring.

3.3.2. Progress in Acoustic Monitoring of Underwater Leakage Oil Droplets

Researchers at home and abroad have carried out investigation and research on acoustic monitoring of underwater oil spills in the Deepwater Horizon, Arctic Ocean Basin and North Sea well sites in the United States to fully verify the feasibility of the application of acoustic technology in this area and to explore the potential of acoustic technology. Currently, research has found that the backscattering property of acoustic technology can be well applied to the monitoring of underwater oil spills. Optical technology can be used to verify the target identity of oil droplets to improve the accuracy of monitoring. At the same time, from the perspective of the attenuation of sound wave, the monitoring of marine sediments can also be applied to the study of underwater oil droplets, and its feasibility can be verified [40,56–59].

Acoustic Backscatter Technology

Some studies have found that after an oil spill, a portion of the leaked substances will rise to form a surface oil slick; in addition, another portion will form oil droplet aggregate and exist in the form of a mixture of oil and sediment in the water (Figure 6) [17]. Scholars have borrowed monitoring techniques from marine sediments and studied the application of acoustic backscattering in underwater oil spill detection, and have practiced it in multiple underwater leak events and experiments. As shown in Table 2, acoustic instruments used in underwater oil spill detection include echo sounders, multibeam sensors, side-scan sonars, and acoustic Doppler current profilers. An echo sounder can identify underwater oil leaks by the changes in acoustic backscattering intensity [59–61]. Multibeam sensors have good target classification and recognition functions, and can provide a three-dimensional diffusion map of oil droplets in the water column [62–64]. Side-scan sonar can quickly monitor large areas of oil spills through the image of acoustic reflectivity [65,66]. The acoustic Doppler current profiler can obtain the dynamic characteristics of oil droplet targets and then estimate the oil spill leakage situation [60,67]. Some acoustic instruments use high-frequency sound waves to monitor underwater oil droplets. High-frequency sound waves propagate over long distances, and can be used in deep water environments and turbid water bodies. They also have a broad monitoring coverage area, which is conducive to capturing underwater oil droplets [62].

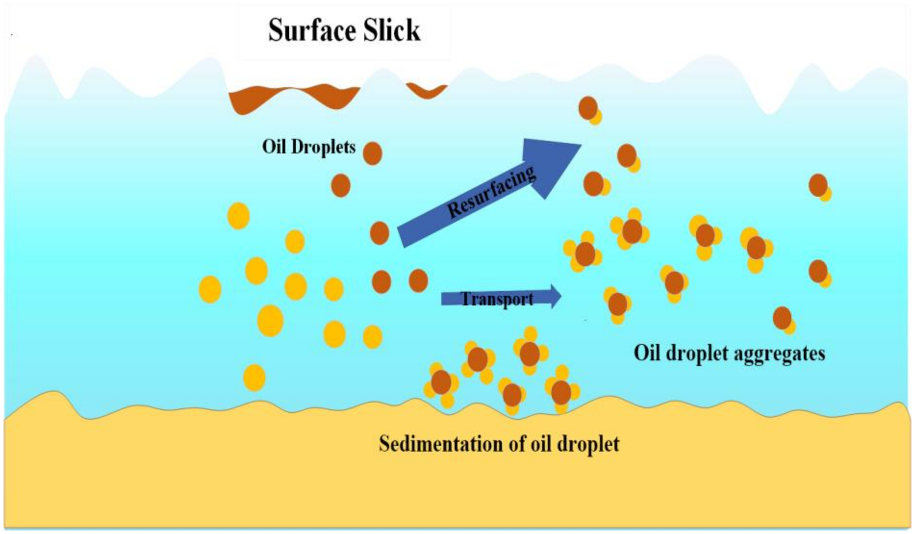

Figure 6. Conceptual model of oil particle aggregate.

Broadband acoustics has a continuous frequency band, which can provide more information about different target bodies. Broadband acoustic backscatter has been used to identify fish species and plankton, among others [68,69]. By using the amplitude and shape of broadband acoustic backscatter, it is possible to differentiate hydrocarbons in leaked substances and determine the flow rate of hydrocarbons, and to estimate the distribution of leaked gas and oil droplets [60]. Acoustic technology has been experimentally verified to detect oil and gas in water columns, but subsequent sampling or fitting of oil droplet and bubble models are necessary to verify and estimate the acoustic characteristics of observed oil droplets, ensuring the accuracy of detection data and improving the sensitivity and reliability of underwater oil spill monitoring.

Table 2. Statistics of oil spill monitored by acoustic technology.

Project Status	Technical Progress	Sound Wave Frequency
Galicia oil spill (2002)	Monitoring of oil spills on the seafloor using multi-beam acoustic backscatter [64].	High frequency
Gulf of Mexico oil spill (2010)	1. Using 1.2 MHz acoustic Doppler current profiler and dual frequency sonar [67]; 2. Shipborne single-wave echo sounder for underwater oil spill monitoring; 3. Combined telescopic fluorescence sensor and broadband multibeam sonar for monitoring [70]; 4. Broadband acoustic backscatter angle study of oil droplet scattering characteristics [71].	1. Low frequency 2. High frequency 3. High frequency 4. High frequency
Ohmsett oil spill monitoring experiment (2013)	Testing the application of multibeam sonar and wide-angle scatter to underwater oil spills [72].	Low frequency
Mississippi River oil spill (2015) Mississippi MC20 oil spill	Acoustic backscatter images of underwater oil droplets using side-scan sonar [65]. Shipboard acoustic observations with ADCP and high-frequency broadband echo sounder to assess liquid and gaseous hydrocarbon flow rates [60].	1. High frequency 2. High frequency
Undersea pipeline leak in Santa Barbara County, California (2016) [26]	Acoustic volume backscatter values for oil and gas in the water column were collected using a partial wave echosounder and calibrated using in situ capture [61].	High frequency

Table 2. *Cont.*

Project Status	Technical Progress	Sound Wave Frequency
Bohai oil sinking event (2018)	Multi-beam sonar is used to detect oil droplets; and backscattering intensity image, which can directly reflect the characteristics of oil droplets, is generated [62].	High frequency
Fuel tank leak in Baltic shipwreck	Multibeam echo sounder backscatter data were used to monitor and investigate the frequency of the acoustic instrument [63].	Low and high frequencies

Oil spill monitoring requires studying the influence of oil droplets on acoustic backscatter characteristics, and droplet size is critical to determining the dispersion of oil in the marine environment. Developing an underwater oil droplet model is an important aspect of solving this problem. In reality, the traditional spherical model is not applicable for oil droplets moving in the deep sea. To improve the accuracy of acoustic monitoring, it is necessary to further improve the oil droplet model and explore underwater oil spill behavior. Researchers have found that oil droplets become elliptical in shape and spiral in their trajectory during floating, which provides support for oil droplet models in deepwater oil spill monitoring [6,73]. Various increasingly complex acoustic scattering studies have been reviewed, such as simplified spherical droplet acoustic scattering models, the effect of crude oil density and sound speed on acoustic scattering under ocean temperature and pressure, the final impact of the degree of deviation of oil droplets from spherical on acoustic scattering, and the prediction of the sizes of leaking oil droplets and bubbles through a fluid particle rising speed model, taking into account the reality of oil spill treatment, such as the status of oil droplets and bubbles under dispersants, and other chemical reagents. The oil droplet target calculation method has been optimized and the underwater oil droplet model has been improved [59,60,70,74].

When a leak occurs underwater, a large amount of gas and oil droplets will mix and spew out. Gas and oil droplets belong to different media, and the complex multiphase plume formed by the oil–gas mixture has dispersed phases of oil droplets and bubbles of different sizes, with seawater as the continuous phase. Bubbles and oil droplets can appear side by side, posing a challenge to deep-sea monitoring. Currently, optical technology is used to separate and monitor deep-sea oil droplets and bubbles, and shadow images are used to obtain information on the motion of oil droplets and bubbles. This method can effectively solve the identification problem of bubbles and oil droplets and has great application value for small-scale oil spills [75]. This also provides a reference idea for using acoustic technology to monitor underwater oil spills. Since a multiphase turbulent flow is formed between seawater and dispersed-phase oil droplets and bubbles, and there is a slip velocity between them, the identification and monitoring can be achieved by using the influence of the multiphase turbulent flow on the sound wave and taking this deviation velocity as a starting point. Studies have been conducted to obtain velocity profiles in oil and water laminar flows using Doppler methods [48,49], as well as instantaneous velocity distributions of liquid and bubble phases in bubble flows; and also to study the motion of oil and gas in seawater from ultrasound and acoustic emission perspectives to obtain its velocity profile, dispersed phase size distribution, and volume fraction [47].

Acousto-Optic Technology Combination

To address the problem of oil droplet size distribution, people consider using optical instruments for direct sampling. Some researchers have combined shipborne hydrographic surveying with direct underwater observation and investigation to monitor oil spills [59,76,77]. The position of the oil spill is determined by the backscatter anomaly point of the acoustic instrument, and sonar technology can provide a three-dimensional diffusion view of spilled oil droplets. Sampling is performed using optical technology, in which the tripod is a structure for fixing the optical sensor and sonar to beam scan the oil layer to determine information about its status. Underwater cameras can be used to transmit monitoring images in the water column. The technology identifies oil droplets and gases, confirms the presence of oil and gases in the sonar images, and provides a comprehensive understanding of hydrocarbon transport routes underwater (Figure 7) [70,78,79]. Figure 8 summarizes the workflow of four acoustic instruments - echosounder, multibeam transducer, sidescan sonar and acoustic doppler current profiler - in monitoring underwater oil spills and the subsequent development of the combination with optical technology. The research results prove that the combination of acoustic and optical instruments is effective in detecting and identifying oil plumes in the water column. However, the deployment and operation of optical sampling instruments are complex and expensive, and are affected by ocean environments such as underwater turbulence, requiring further research for improvement [80]. Sampling is performed using equipment with an optical sampling device, where the tripod is a structure with fixed optical sensors and sonar, and beam scanning of the oil layer to determine its status information. Underwater cameras can be used to transmit monitoring images in the water body.

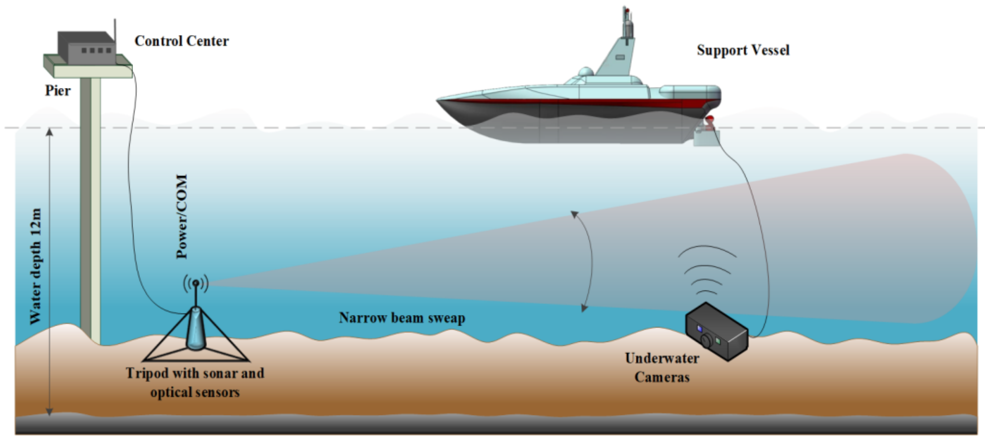

Figure 7. Acousto-optic technology monitoring.

3.3.3. Active and Passive Acoustic Detection of Oil Spills

Active and passive detection are different exploration methods for deep-sea oil spill monitoring. Active detection refers to the analysis of the movement of oil droplets and gases according to the echoes by emitting sound waves into oil droplets and gases in the deep sea [81]. Active acoustic detection is commonly used for underwater oil droplet and low solubility gas monitoring [60–63,67,73,82,83]. However, active detection requires higher working power and is suitable for short-time-period monitoring, while deep-sea oil spill monitoring requires a longer working period. In terms of energy consumption, active acoustic detection has greater limitations.

Passive detection, on the other hand, refers to the analysis of the dynamic information through the sound wave signals emitted by oil droplets and bubbles. Passive acoustic technology can obtain continuous motion information of the target body and is simple in equipment and low in cost, making it suitable for long-term monitoring. Currently, passive detection technology is widely researched in underwater gas monitoring. Passive acoustic detection is mainly conducted by hydrophones to monitor the sound generated by underwater bubbles, and in the case of a single gas, a method based on bubble feature identification is used. When dealing with gas leakage in the form of plumes, hydrophone arrays are used to quantify the leakage. However, passive acoustic detection is easily affected by underwater noise, resulting in ineffective monitoring. To solve this problem, some scholars have summarized the noise-impact assessment model of passive acoustic measurement, finite element model of underwater gas escape process, etc., which improves the noise resistance of measurement technology and abates the influence of ocean noise on acoustic monitoring. It can be seen that passive acoustic techniques are feasible in monitoring underwater gases [84–88].

Currently, active acoustic detection is widely used in underwater oil spill monitoring, while research on passive acoustic technology for oil droplet monitoring is limited domestically and internationally. This field needs further exploration. Both active and passive acoustic technologies have advantages and limitations in monitoring underwater oil spills, and a cross-comparison of the two can verify their effectiveness and feasibility in monitoring underwater gas and oil droplets.

In existing studies, the monitoring of underwater oil spills using acoustic techniques has been carried out after a spill has occurred. In future marine oil and gas operations, monitoring systems should be deployed in advance within and around the offshore petroleum and natural gas systems to enable real-time monitoring.

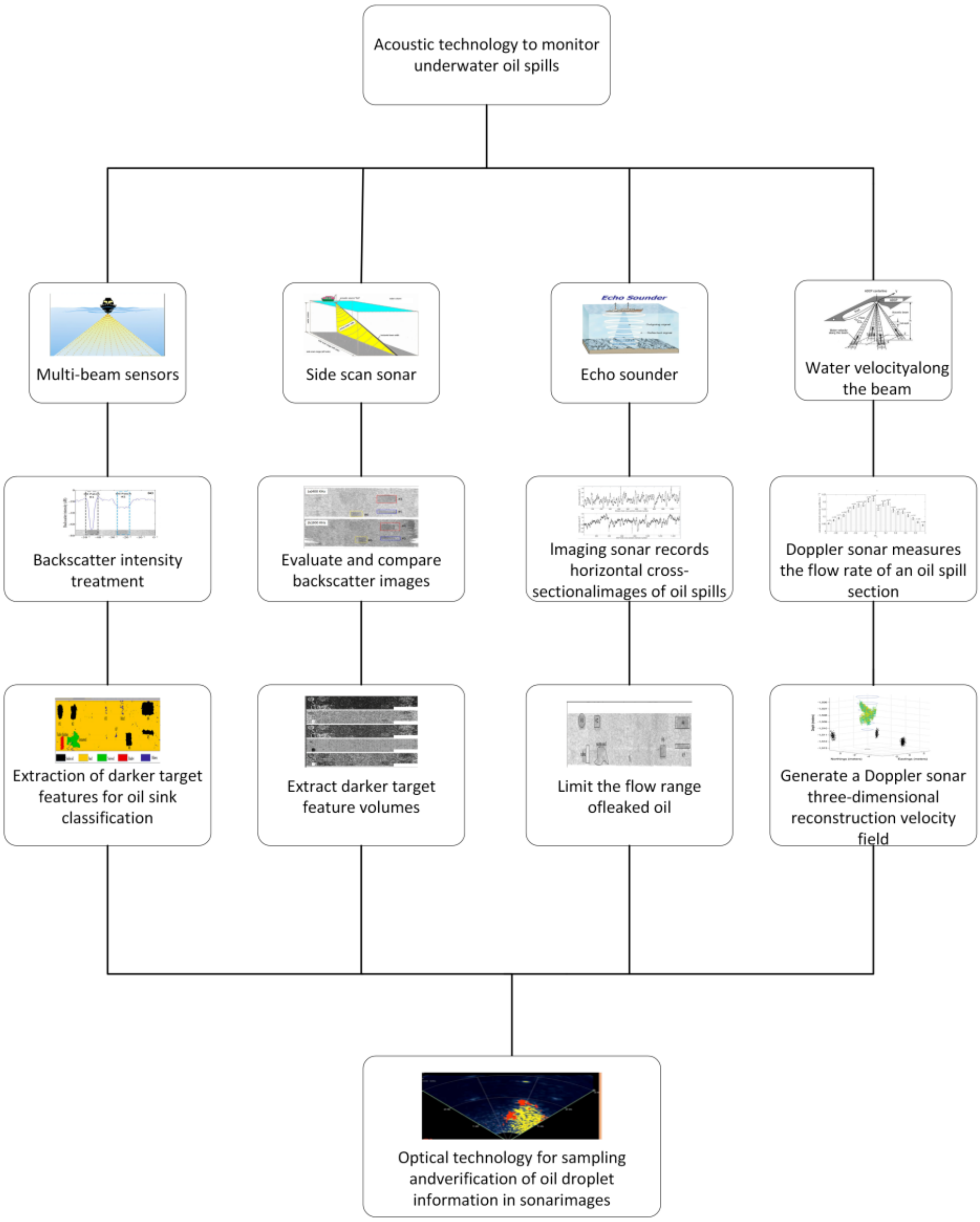

Figure 8. Four kinds of acoustic instruments oil spill monitoring process.

4. The Advantages of Acoustic Detection Systems

4.1. High Precision

Compared to light and electromagnetic wave, the propagation of low-frequency sound wave in seawater is less affected by seawater and can not only meet the long-distance transmission, but also ensure the accuracy of the transmission process. If multiple acoustic emission points and signal reception points are placed in the oil spill monitoring area to form a sensor network, large-scale observations can be made along the acoustic propagation path in the ocean, and the more emission and reception points there are, the more information on the dynamics of oil droplets along the propagation path can be obtained and the higher the spatial resolution.

4.2. Modular Development

The monitoring system adopts a modular design scheme, mainly including control modules, power supply modules, communication modules, and various observation modules. It can achieve multi-aspect monitoring of marine targets. Each module has its own responsibilities, which effectively improves the efficiency and accuracy in the monitoring process. The oil spill acoustic monitoring module can learn from the development of other acoustic monitoring systems, such as the modular design of the ice and sea interface acoustic monitoring system applicable to the polar regions, which not only has the operating efficiency of the monitoring system improved, but it is also conducive to the debugging and inspection of the monitoring system [89]. The oil spill acoustic monitoring system is oriented towards modular development, which can further improve the efficiency of oil spill monitoring.

4.3. Good Stability

Compared to other forms of energy such as electromagnetic waves, sound waves are minimally absorbed by seawater, especially low-frequency sound waves, which can propagate over long distances and receive a higher quality sound-wave signal. Due to the dynamic and irreproducible nature of the marine environment, acoustic technology has good precision and stability, and is more suitable for application in marine detection.

5. Future Prospects for Oil Spill Monitoring Technology

Currently, oil spill monitoring is continuously evolving, gradually achieving intelligence, systematization, and integration. In the future, the development of acoustic technology in oil spill monitoring can be improved from the technical level, monitoring schemes and monitoring methods, enhancing the applicability of acoustic technology in oil spill monitoring. Additionally, integrating acoustic technology with oil spill trajectory simulation can provide better detection tools for oil spill response and risk assessment [90].

5.1. Intelligent Detection

The future development of acoustic technology will be deeply integrated with unmanned submersible technology, as the marine environment is very complex and presents certain risks and challenges. As shown in Table 3, research has already explored intelligent acoustic monitoring through experimental exploration, using underwater vehicles equipped with acoustic technology for in situ measurements in harsh environments (Figure 9), to achieve real-time simulation of the three-dimensional structure of oil and gas plumes [90–92]. Figure 10 shows the structure of the acoustic equipment carried by ROVs. The underwater vehicle sends information on the status of subsea oil spills to support ships via underwater communication, and after automatically floating to the surface, sends information on the location of the spill. This connects the underwater acoustic communication network with the oil spill monitoring platform, providing guidance and assistance for global marine oil industry oil spill emergency response [10,93,94].

Table 3. Research on intelligent acoustic monitoring.

Status of the Project	Technical Progress
Acoustic monitoring of methane seeps in the northern Gulf of Mexico	The ROV used a combination of multi-beam and split-beam echo sounders to map methane seepage [95].
Applications for mapping spilled oil in Arctic waters	Technique for measuring oil slick thickness and bubble/oil droplet size using an electro-acoustic transducer in conjunction with an ROV and AUV [72].
Acoustic oil spill detection and mapping under Arctic sea ice using an autonomous underwater vehicle	The ROV is coupled with high-frequency sonar to provide quantitative information on acoustic scatterers such as oil droplets [96].
Eu Horizon Research project integrated oil spill emergency response	The underwater vehicle monitors oil spills in situ to improve the ability to monitor oil spills in real time [97].
The experiment uses bubbles as proxies for oil droplets to test the AUV monitoring of oil spills	Verify the feasibility of sonar to capture gas in the water column [91].

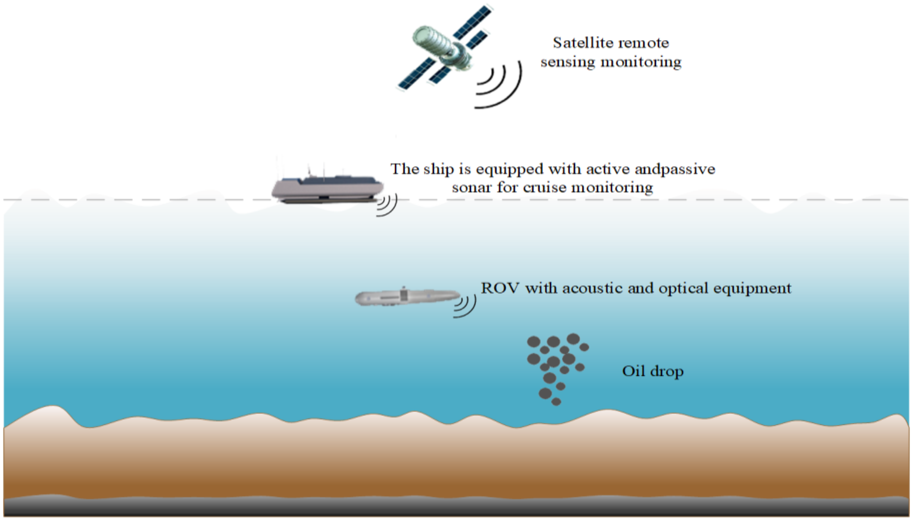

Figure 9. Shipboard acoustic monitoring and underwater robotic monitoring of oil spills.

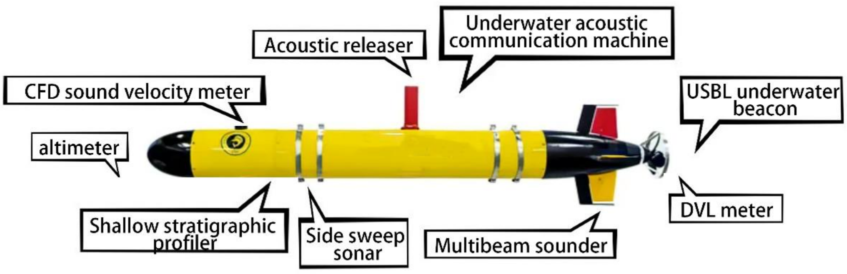

Figure 10. Underwater robots equipped with multiple acoustic detectors.

5.2. Active Detection and Passive Detection Techniques Are Combined

Water acoustic monitoring technology is achieving a monitoring mode that combines active detection with passive detection [98]. When pressurized oil and gas leak from the subsea oil pipeline, it will suddenly expand and release, generating sound wave. A passive detection mode can be used to monitor and locate the oil and gas injection position using acoustic instruments such as hydrophones. For the diffusion of oil and gas in water, a sonar array can be used to achieve high-resolution scanning and detection of the oil spill source. The sonar emits sound wave towards targets such as oil droplets, receives echo signals, and, thus, can obtain real-time information on their movement and the formation of oil slicks.

6. Conclusions

Acoustic technology is of great significance for underwater oil spill monitoring. Compared with other technologies such as optics, the feasibility of acoustic monitoring in this area is relatively high and has received extensive attention from scholars. Underwater oil spill emergency monitoring is an extremely complex engineering problem, and solving the problem of underwater oil spill monitoring is of extraordinary significance for oil spill emergency response. Through a survey and summary of domestic and foreign underwater oil spill monitoring methods, it was found that although many research results have been achieved in the key technologies for underwater target detection based on acoustic technology, there are still some problems that can be addressed in the following areas.

The first aspect is to optimize the monitoring effectiveness of acoustic technology, which can be enhanced through research on technical indicators, program deployment, and data analysis. After an oil spill event, oil droplets will spread in the form of a plume. When acoustics is used for remote plume measurement, the pulse length and bandwidth should be adjusted, and a relatively small bandwidth and long acoustic pulse can be selected to monitor the plume consisting of individual oil droplet scatterers to enhance the applicability and feasibility of acoustic technology in underwater oil spill monitoring [83].

Secondly, there is the issue of monitoring oil droplets and bubbles. During underwater oil spill monitoring, it is necessary to classify and identify gases and oil droplets. The acoustic backscatter strength of bubbles and oil droplets in seawater is different. The acoustic impedance of oil droplets and seawater are similar, and the scattering characteristics of oil droplets are weaker compared to the high scattering characteristics of bubbles [90,99]. Solving the acoustic scattering problem of oil droplets can help to improve underwater oil spill monitoring. Research has found that the difference in target strength between oil droplets and bubbles is significant at low frequencies. Attempts can be made in a wider frequency range to help detect the characteristics of individual oil droplets to determine their size and identity [90]. Meanwhile, the velocity and other motions of the oil phase can be studied using ultrasonic Doppler technology based on the multi-phase floating jet model formed between oil droplets, bubbles, and seawater [45,47]. Currently, this research area is relatively scarce and can serve as a breakthrough point for underwater oil spill acoustic monitoring.

In addition, studying the impact of marine environmental factors and practical conditions for oil spill treatment on the acoustic properties and status of oil droplets is also an important task for optimizing monitoring. The deep-sea environment is complex and there are interfering factors such as sound and light that can affect monitoring effectiveness. The next research needs to use acoustic technology to overcome the limitations of the underwater environment and achieve real-time monitoring of underwater oil spills. Further exploring the potential of acoustic technology in the field of marine detection is of great significance for the development of emergency response to marine oil spills [100].

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References

1. Chen, Q.S.; Hu, S. A study of marine oil spills along the Chinese offshore coast. *Mar. Dev. Manag.* **2020**, *37*, 49–53.
2. Amir-Heidari, P.; Raie, M. Probabilistic risk assessment of oil spill from offshore oil wells in Persian Gulf. *Mar. Pollut. Bull.* **2018**, *136*, 291–299. [CrossRef] [PubMed]
3. Chiri, H.; Abascal, A.J.; Castanedo, S. Deep oil spill hazard assessment based on spatio-temporal met-ocean patterns. *Mar. Pollut. Bull.* **2020**, *154*, 111123. [CrossRef]
4. Meza-Padilla, R.; Enriquez, C.; Appendini, C.M. Rapid assessment tool for oil spill planning and contingencies. *Mar. Pollut. Bull.* **2021**, *166*, 112196. [CrossRef] [PubMed]
5. Li, H.; Meng, L.; Shen, T.; Zhang, J.; Bao, M.; Sun, P. The formation process and responsive impacts of single oil droplet in submerged process. *Mar. Pollut. Bull.* **2017**, *124*, 139–146. [CrossRef]
6. Ji, H.; Xu, M.; Huang, W.; Yang, K. The influence of oil leaking rate and ocean current velocity on the migration and diffusion of underwater oil spill. *Sci. Rep.* **2020**, *10*, 9226. [CrossRef]
7. Li, X.; Zhu, Y.; Wang, J.; Zhang, R.; Chen, G. Dispersion modeling of underwater oil released from buried subsea pipeline considering current and wave. *Ocean. Eng.* **2023**, *272*, 113924. [CrossRef]
8. Zhu, Z.; Merlin, F.; Yang, M.; Lee, K.; Chen, B.; Liu, B.; Cao, Y.; Song, X.; Ye, X.; Li, Q.K.; et al. advances in chemical and biological degradation of spilled oil: A review of dispersants application in the marine environment. *J. Hazard. Mater.* **2022**, *436*, 129260. [CrossRef]
9. Adofo, Y.K.; Nyankson, E.; Agyei-Tuffour, B. Dispersants as an oil spill clean-up technique in the marine environment: A review. *Heliyon* **2022**, *8*, e10153. [CrossRef]
10. Yan, J.; De, Z. Design and implementation of real-time monitoring system for marine spills. *Foreign Electron. Meas. Technol.* **2019**, *38*, 153–156.
11. Ma, X.; Xu, J.; Pan, J.; Yang, J.; Wu, P.; Meng, X. Detection of marine oil spills from radar satellite images for the coastal ecological risk assessment. *J. Environ. Manag.* **2023**, *325*, 116637. [CrossRef] [PubMed]
12. Kato, N.; Senga, H.; Suzuki, H. Autonomous Spilled Oil and Gas Tracking Buoy System and Application to Marine Disaster Prevention System: Part 1. In *SPE Annual Technical Conference and Exhibition*; OnePetro: San Antonio, TX, USA, 2012; pp. 1–3.
13. Zhang, T.; Qin, S.; Tang, J.; Wang, X.; Li, Z. Technical Status and Development Trend of Vessel-Mount Long Rang Acoustic Doppler Current Profiler. *Ship Electron. Eng.* **2019**, *39*, 146–149.
14. Brandvik, P.J.; Davies, E.; Leirvik, F.; Johansen, Ø.; Belore, R. Large-scale basin testing to simulate realistic oil droplet distributions from subsea release of oil and the effect of subsea dispersant injection. *Mar. Pollut. Bull.* **2021**, *163*, 111934. [CrossRef] [PubMed]
15. Cooper, C.; Adams, E.; Gros, J. An evaluation of models that estimate droplet size from subsurface oil releases. *Mar. Pollut. Bull.* **2021**, *163*, 111932. [CrossRef]
16. Qi, J.; Li, J.; An, W.; Zhao, Y.; Chen, H. Study on the behavior and fate of underwater oil spills in deepwater areas. *Ocean. Dev. Manag.* **2013**, *30*, 77–84.
17. Gustitus, S.A.; Clement, T.P. Formation, Fate, and Impacts of Microscopic and Macroscopic Oil-Sediment Residues in Nearshore Marine Environments: A Critical Review. *Rev. Geophys.* **2017**, *55*, 1130–1157. [CrossRef]
18. Qi, Z.; Yu, Y.; Yu, X.; Li, X.; Fu, S.; Xiong, D. Effect of the concentration and size of suspended particulate matter on oil-particle aggregation. *Mar. Pollut. Bull.* **2020**, *153*, 110957. [CrossRef]
19. Jacketti, M.; Beegle-Krause, C.J.; Englehardt, J.D. A review on the sinking mechanisms for oil and successful response technologies. *Mar. Pollut. Bull.* **2020**, *160*, 111626. [CrossRef]
20. Wang, L.; Xin, L.; Yu, B.; Ju, L.; Wei, L. A novel method for determination of the oil slick area based on visible and thermal infrared image fusion. *Infrared Phys. Technol.* **2021**, *119*, 103915. [CrossRef]
21. Ivanov, A.Y.; Kucheiko, A.Y.; Ivonin, D.V.; Filimonova, N.A.; Terleeva, N.V.; Evtushenko, N.V. Oil spills in the Barents Sea: The results of multiyear monitoring with synthetic aperture radar. *Mar. Pollut. Bull.* **2022**, *179*, 113677. [CrossRef]
22. Lipscombe, R. Australia's tyranny of distance in oil spill response. *Spill Sci. Technol. Bull.* **2000**, *6*, 13–25. [CrossRef]
23. Yapa, P.D.; Wimalaratne, M.R.; Dissanayake, A.L.; DeGraff Jr, J.A. How does oil and gas behave when released in deepwater? *J. Hydro-Environ. Res.* **2012**, *6*, 275–285. [CrossRef]
24. Jiang, J. Dual Plume Integration Model and Its Application in Subsea Oil Spill Simulation. Master's Thesis, Tsinghua University, Beijing, China, 2017.
25. Wang, C.; Liang, F.; He, Z.; Zhao, F.; Wang, M. The law of diffusion and migration of oil spill from submarine pipeline under wave action. *Hebei J. Ind. Sci. Technol.* **2021**, *38*, 172–179.
26. Leifer, I. A Synthesis Review of Emissions and Fates for the Coal Oil Point Marine Hydrocarbon Seep Field and California Marine Seepage. *Geofluids* **2019**, *2019*, 4724587. [CrossRef]
27. De Kerf, T.; Gladines, J.; Sels, S.; Vanlanduit, S. Oil Spill Detection Using Machine Learning and Infrared Images. *Remote Sens.* **2020**, *12*, 4090. [CrossRef]
28. Cong, H. Characteristics of UV Reflection Spectra of Oil Spill Based on Bidirection Reflectance Distribution Function. *Acta Photonica Sin.* **2017**, *46*, 170–178.
29. Bai, F. Research on Oil Spill Monitoring Technology for Water Surface Based on Fluorescence Mechanism. Master's Thesis, National Marine Technology Center, Anacortes, WA, USA, 2019.

30. Araújo, K.C.; Barreto, M.C.; Siqueira, A.S.; Freitas, A.C.P.; Oliveira, L.G.; Bastos, M.E.P.A.; Rocha, M.E.P.; Silva, L.A.; Fragoso, W.D. Oil spill in northeastern Brazil: Application of fluorescence spectroscopy and PARAFAC in the analysis of oil-related compounds. *Chemosphere* **2021**, *267*, 129154. [CrossRef]
31. Fingas, M.; Brown, C. A Review of Oil Spill Remote Sensing. *Sensors* **2018**, *18*, 91. [CrossRef]
32. Sun, L.; Zhang, Y.; Ouyang, C.; Yin, S.; Ren, X.; Fu, S. A portable UAV-based laser-induced fluorescence lidar system for oil pollution and aquatic environment monitoring. *Opt. Commun.* **2023**, *527*, 128914. [CrossRef]
33. Pelta, R.; Carmon, N.; Ben-Dor, E. A machine learning approach to detect crude oil contamination in a real scenario using hyperspectral remote sensing. *Int. J. Appl. Earth Obs. Geoinf.* **2019**, *82*, 101901. [CrossRef]
34. Zhang, T.; Jie, G. SAR image oil spill detection method based on improved Faster R-CNN model. *Mar. Sci.* **2021**, *45*, 103–112.
35. De Padova, D.; Mossa, M.; Adamo, M.; De Carolis, G.; Pasquariello, G. Synergistic use of an oil drift model and remote sensing observations for oil spill monitoring. *Environ. Sci. Pollut. Res. Int.* **2017**, *24*, 5530–5543. [CrossRef] [PubMed]
36. Al-Ruzouq, R.; Gibril, M.B.A.; Shanableh, A.; Kais, A.; Hamed, O.; Al-Mansoori, S.; Khalil, M.A. Sensors, Features, and Machine Learning for Oil Spill Detection and Monitoring: A Review. *Remote Sens.* **2020**, *12*, 3338. [CrossRef]
37. Marghany, M. Chapter 11—Automatic detection of oil spills from SAR satellite data using genetic algorithm. In *Synthetic Aperture Radar Imaging Mechanism for Oil Spills*; Marghany, M., Ed.; Gulf Professional Publishing: Woburn, MA, USA, 2020; pp. 187–215.
38. Huang, X.; Zhang, B.; Perrie, W.; Lu, Y.; Wang, C. A novel deep learning method for marine oil spill detection from satellite synthetic aperture radar imagery. *Mar. Pollut. Bull.* **2022**, *179*, 113666. [CrossRef]
39. Kuperman, W.; Roux, P. Underwater acoustics 2007. In *Springer Handbook of Acoustics*; Springer: Berlin/Heidelberg, Germany, 2007; pp. 149–204.
40. Panetta, P.D.; Bland, L.G.; Cartwright, G.; Friedrichs, C.T. Acoustic scattering to measure dispersed oil droplet size and sediment particle size. In *2012 Oceans*; IEEE: Piscataway, NJ, USA, 2012.
41. Luo, J.; Han, Y.; Fan, L. Underwater acoustic target tracking: A review. *Sensors* **2018**, *18*, 112. [CrossRef]
42. Manik, H.M. Underwater acoustic detection and signal processing near the seabed. In *Sonar Systems 2011*, 1st ed.; Kolev, N., Ed.; InTech: Rijeka, Croatia, 2011; pp. 255–274.
43. Bjørnø, L.; Neighbors, T.; Bradley, D. *Applied Underwater Acoustics*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 346–348.
44. Wang, R. Research on Acoustic Detection Technology of Underwater Bionic Target with Optical Fiber. Master's Thesis, Heilongjiang University, Harbin, China, 2021.
45. Manik, H.M.; Furusawa, M.; Amakasu, K. Measurement of sea bottom surface backscattering strength by quantitative echo sounder. *Fish. Sci.* **2006**, *72*, 503–512. [CrossRef]
46. Hu, H. Research on Acoustic-Based Ocean Hydrothermal/Cold Spring Detection Technology. Master's Thesis, Hangzhou Dianzi University, Hangzhou, China, 2015.
47. Hossein, F.; Materazzi, M.; Lettieri, P.; Angeli, P. Application of acoustic techniques to fluid-particle systems—A review. *Chem. Eng. Res. Des.* **2021**, *176*, 180–193. [CrossRef]
48. Dong, X.; Tan, C.; Yuan, Y.; Dong, F. Oil–water two-phase flow velocity measurement with continuous wave ultrasound Doppler. *Chem. Eng. Sci.* **2015**, *135*, 155–165. [CrossRef]
49. Liu, W.; Tan, C.; Dong, F. Oil-water two-phase flow velocity measurement with Continuous wave ultrasonic Doppler. *J. Phys. Conf. Ser.* **2018**, *1065*, 092019. [CrossRef]
50. Jordt, A.; Zelenka, C.; Von Deimling, J.S.; Koch, R.; Köser, K. The Bubble Box: Towards an Automated Visual Sensor for 3D Analysis and Characterization of Marine Gas Release Sites. *Sensors* **2015**, *15*, 30716–30735. [CrossRef]
51. She, M.; Weiß, T.; Song, Y.; Urban, P.; Greinert, J.; Köser, K. Marine bubble flow quantification using wide-baseline stereo photogrammetry. *ISPRS J. Photogramm. Remote Sens.* **2022**, *190*, 322–341. [CrossRef]
52. Jerram, K.; Weber, T.C.; Beaudoin, J. Split-beam echo sounder observations of natural methane seep variability in the northern Gulf of Mexico. *Geochem. Geophys. Geosystems* **2015**, *16*, 736–750. [CrossRef]
53. Kannberg, P.K.; Tréhu, A.M.; Pierce, S.D.; Paull, C.K.; Caress, D.W. Temporal variation of methane flares in the ocean above Hydrate Ridge, Oregon. *Earth Planet. Sci. Lett.* **2013**, *368*, 33–42. [CrossRef]
54. Nishimura, K.U.; Xue, Z.; Watanabe, Y. A preliminary experiment on the detection of bubbles in the sea with side-scan sonar. In Proceedings of the 14th Greenhouse Gas Control Technologies Conference, Melbourne, Australia, 21–26 October 2018.
55. Wen, R.; Sinding-Larsen, R. Mapping Oil Seeps on the Sea Floor by Gloria Side-Scan Sonar ImagesmA Case Study from the Northern Gulf of Mexico. *Nonrenewable Resour.* **1996**, *5*, 141–154. [CrossRef]
56. Carpenter, W.O.; Goodwiller, B.T.; Wren, D.G.; Taylor, J.; AuBuchon, J.; Brown, J. Field testing a High-Frequency acoustic attenuation system for measuring fine suspended sediments and algal movements. *Appl. Acoust.* **2022**, *198*, 108980. [CrossRef]
57. Sahin, C. Effect of particle size distribution on Acoustic Doppler Velocimeter backscatter for suspended sediment measurements. *Flow Meas. Instrum.* **2021**, *79*, 101953. [CrossRef]
58. Sahin, C.; Ozturk, M.; Aydogan, B. Acoustic doppler velocimeter backscatter for suspended sediment measurements: Effects of sediment size and attenuation. *Appl. Ocean. Res.* **2020**, *94*, 101975. [CrossRef]
59. Weber, T.C.; De Robertis, A.; Greenaway, S.F.; Smith, S.; Mayer, L.; Rice, G. Estimating oil concentration and flow rate with calibrated vessel-mounted acoustic echo sounders. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 20240–20245. [CrossRef]
60. Loranger, S.; Weber, T.C. Shipboard Acoustic Observations of Flow Rate from a Seafloor-Sourced Oil Spill. *J. Geophys. Res. Ocean.* **2020**, *125*, e2020JC016274. [CrossRef]

61. Padilla, A.M.; Loranger, S.; Kinnaman, F.S.; Valentine, D.L.; Weber, T.C. Modern Assessment of Natural Hydrocarbon Gas Flux at the Coal Oil Point Seep Field, Santa Barbara, California. *J. Geophys. Res. Ocean.* **2019**, *124*, 2472–2484. [CrossRef]
62. Li, J.; An, W.; Xu, C.; Hu, J.; Gao, H.; Du, W.; Li, X. Sunken oil detection and classification using MBES backscatter data. *Mar. Pollut. Bull.* **2022**, *180*, 113795. [CrossRef] [PubMed]
63. Szafrańska, M.; Gil, M.; Nowak, J. Toward monitoring and estimating the size of the HFO-contaminated seabed around a shipwreck using MBES backscatter data. *Mar. Pollut. Bull.* **2021**, *171*, 112747. [CrossRef] [PubMed]
64. Medialdea, T.; Somoza, L.; León, R.; Farrán, M.; Ercilla, G.; Maestro, A. Multibeam backscatter as a tool for sea-floor characterization and identification of oil spills in the Galicia Bank. *Mar. Geol.* **2008**, *249*, 93–107. [CrossRef]
65. Schweitzer, T.M.; Michel, J. Application of Sonar For Oil Spill Response Acoustic Detection, Evaluation and Monitoring of Sunken Oil Spills. *Sea Technol.* **2016**, *57*, 10.
66. Hansen, K.; Fitzpatrick, M.; Vanhaverbeke, M. *Heavy Oil Detection (Prototypes) Final Report*; Defense Technical Information Center: Fort Belvoir, VA, USA, 2009.
67. Camilli, R.; Di Iorio, D.; Bowen, A.; Reddy, C.M.; Techet, A.H.; Yoerger, D.R.; Fenwick, J. Acoustic measurement of the Deepwater Horizon Macondo well flow rate. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 20235–20239. [CrossRef]
68. Kubilius, R.; Bergès, B.; Macaulay, G.J. Remote acoustic sizing of tethered fish using broadband acoustics. *Fish. Res.* **2023**, *260*, 106585. [CrossRef]
69. Briseño-Avena, C.; Roberts, P.L.; Franks, P.J.; Jaffe, J.S. ZOOPS-O2: A broadband echosounder with coordinated stereo optical imaging for observing plankton in situ. *Methods Oceanogr.* **2015**, *12*, 36–54. [CrossRef]
70. Pocwiardowski, J.B.E. Oil Leak Detections with a Combined Telescopic Fluorescence Sensor and a Wide Band MultiBeam Sonar. In Proceedings of the International Oil Spill Conference Proceedings, Long Beach, CA, USA, 15–18 May 2017.
71. Loranger, S.; Pedersen, G.; Weber, T.C. Broadband acoustic scattering from oblate hydrocarbon droplets. *J. Acoust. Soc. Am.* **2019**, *146*, 1176–1188. [CrossRef]
72. Paul, D.; Panetta, T.A.H.D. Development of acoustic methods to measure oil droplet size and slick thickness on ROV and AUV platforms. In *Bureau of Safety and Engineering Enforcement*; United States Department of the Interior: Washington, DC, USA, 2017.
73. Chen, H.; An, W.; You, Y.; Lei, F.; Zhao, Y.; Li, J. Numerical study of underwater fate of oil spilled from deepwater blowout. *Ocean. Eng.* **2015**, *110*, 227–243. [CrossRef]
74. Niu, X.; Hao, J. Multi-Phase Floating Jet Experiment Generation Device and Oil Droplet Bubble Shadow Image Processing Method: Beijing. Chinese Patent CN108548817B, 3 August 2021.
75. Loranger, S.; Bassett, C.; Cole, J.P.; Boyle, B.; Weber, T.C. Acoustically relevant properties of four crude oils at oceanographic temperatures and pressures. *J. Acoust. Soc. Am.* **2018**, *144*, 2926–2936. [CrossRef]
76. Römer, M.; Hsu, C.W.; Loher, M.; MacDonald, I.R.; dos Santos Ferreira, C.; Pape, T.; Sahling, H. Amount and Fate of Gas and Oil Discharged at 3400 m Water Depth From a Natural Seep Site in the Southern Gulf of Mexico. *Front. Mar. Sci.* **2019**, *6*, 700. [CrossRef]
77. Veloso-Alarcón, M.E.; Urban, P.; Weiss, T.; Köser, K.; She, M.; Greinert, J. Quantitatively Monitoring Bubble-Flow at a Seep Site Offshore Oregon: Field Trials and Methodological Advances for Parallel Optical and Hydroacoustical Measurements. *Front. Earth Sci.* **2022**, *10*, 1161. [CrossRef]
78. Wang, B.; Socolofsky, S.A. A deep-sea, high-speed, stereoscopic imaging system for in situ measurement of natural seep bubble and droplet characteristics. *Deep. Sea Res. Part I Oceanogr. Res. Pap.* **2015**, *104*, 134–148. [CrossRef]
79. Desai, P.D.; Ng, W.C.; Hines, M.J.; Riaz, Y.; Tesar, V.; Zimmerman, W.B. Comparison of Bubble Size Distributions Inferred from Acoustic, Optical Visualisation, and Laser Diffraction. *Colloids Interfaces* **2019**, *3*, 65. [CrossRef]
80. Baykal, Y.; Ata, Y.; Gökçe, M.C. Underwater turbulence, its effects on optical wireless communication and imaging: A review. *Opt. Laser Technol.* **2022**, *156*, 108624. [CrossRef]
81. Eriksen, P.K. Leakage and oil spill detection utilizing active acoustic systems. In Proceedings of the 2013 IEEE International Underwater Technology Symposium (UT) 2013, Tokyo, Japan, 5–8 March 2013; pp. 1–8.
82. Turco, F.; Ladroit, Y.; Watson, S.J.; Seabrook, S.; Law, C.S.; Crutchley, G.J.; Gorman, A.R.; Mountjoy, J.; Pecher, I.A.; Hillman, J.I.T.; et al. Estimates of Methane Release from Gas Seeps at the Southern Hikurangi Margin, New Zealand. *Front. Earth Sci.* **2022**, *10*. [CrossRef]
83. Blomberg, A.E.A.; Sæbø, T.O.; Hansen, R.E.; Pedersen, R.B.; Austeng, A. Automatic Detection of Marine Gas Seeps Using an Interferometric Sidescan Sonar. *IEEE J. Ocean. Eng.* **2017**, *42*, 590–602. [CrossRef]
84. Zhang, Y.; Yu, Y.; Rui, X.; Feng, Z.; Zhang, J.; Chen, Y.; Zhou, X. Underwater bubble escape volume measurement based on passive acoustic under noise factors: Simulation and experimental research. *Measurement* **2023**, *207*, 112400. [CrossRef]
85. Longo, M.; Lazzaro, G.; Caruso, C.G.; Radulescu, V.; Radulescu, R.; Sciré Scappuzzo, S.S.; Italiano, F. Black Sea Methane Flares From the Seafloor: Tracking Outgassing by Using Passive Acoustics. *Front. Earth Sci.* **2021**, *9*, 678834. [CrossRef]
86. Li, J.; White, P.R.; Bull, J.M.; Leighton, T.G. A noise impact assessment model for passive acoustic measurements of seabed gas fluxes. *Ocean. Eng.* **2019**, *183*, 294–304. [CrossRef]
87. Bergès, B.J.P.; Leighton, T.G.; White, P.R. Passive acoustic quantification of gas fluxes during controlled gas release experiments. *Int. J. Greenh. Gas Control.* **2015**, *38*, 64–79. [CrossRef]
88. Leighton, T.G.; White, P.R. Quantification of undersea gas leaks from carbon capture and storage facilities, from pipelines and from methane seeps, by their acoustic emissions. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2012**, *468*, 485–510. [CrossRef]

89. Cui, K.; Li, B.; Dou, Y.; Zou, G.; Zhang, H. Design and Development of Ice-Ocean Interface Acoustic Monitorin System. *Chin. J. Electron Devices* **2020**, *43*, 1152–1157+1172.
90. Ji, C.; Beegle-Krause, C.J.; Englehardt, J.D. Formation, Detection, and Modeling of Submerged Oil: A Review. *J. Mar. Sci. Eng.* **2020**, *8*, 642. [CrossRef]
91. Wang, Y.; Thanyamanta, W.; Bulger, C.; Bose, N. Experimental study to make gas bubbles as proxies for oil droplets to test AUV detection of oil plumes. *Appl. Ocean. Res.* **2022**, *121*, 103080. [CrossRef]
92. Wen, X.; Jie, C.; Peng, X. AUV-mounted oil spill detection device for subsea oil pipelines. *Ship Sci. Technol.* **2017**, *39*, 105–110.
93. Li, H.; Wang, G.; Li, W.; Li, C.; Pan, S.; Dong, J. Introduction to the China Integrated Offshore Oil Spill Forecasting and E Warning System. *Mar. Inf.* **2018**, *33*, 44–49.
94. Mohammadiun, S.; Hu, G.; Gharahbagh, A.A.; Li, J.; Hewage, K.; Sadiq, R. Intelligent computational techniques in marine oil spill management: A critical review. *J. Hazard. Mater.* **2021**, *419*, 126425. [CrossRef]
95. Weber, T.C.; Mayer, L.; Jerram, K.; Beaudoin, J.; Rzhanov, Y.; Lovalvo, D. Acoustic estimates of methane gas flux from the seabed in a 6000 km2 region in the Northern Gulf of Mexico. *Geochem. Geophys. Geosystems* **2014**, *15*, 1911–1925. [CrossRef]
96. Ted Maksym, H.S.C.B.; Andone Lavery, L.F.F.S. *Oil Spill Detection and Mapping under Arctic Sea Ice Using Autonomous Underwater Vehicles*; Woods Hole Oceanographic Institution: Woods Hole, MA, USA, 2014.
97. Jørgensen, K.S.; Kreutzer, A.; Lehtonen, K.K.; Kankaanpää, H.; Rytkönen, J.; Wegeberg, S.; Gustavson, K.; Fritt-Rasmussen, J.; Truu, J.; Kõuts, T.; et al. The EU Horizon 2020 project GRACE: Integrated oil spill response actions and environmental effects. *Environ. Sci. Eur.* **2019**, *31*, 44. [CrossRef]
98. Zhang, C.; Xiao, F. Overview of Data Acquisition Technology in Underwater Acoustic Detection. *Procedia Comput. Sci.* **2021**, *188*, 130–136. [CrossRef]
99. Loranger, S. Acoustic Detection and Quantification of Crude Oil. Ph.D. Thesis, University of New Hampshire, Durham, NH, USA, 2019; p. 2456.
100. Yang, Z.; Huo, L.; Wang, J.; Zhou, J. Denoising low SNR percussion acoustic signal in the marine environment based on the LMS algorithm. *Measurement* **2022**, *202*, 111848. [CrossRef]