Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Research Progress in Marine Environmental Monitoring Technology

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ABSTRACT

Marine environmental monitoring and data platform technology plays a pivotal role in advancing marine scientific research, sustainable resource development, ecological conservation, and the effective utilization of ocean resources. Despite its growing importance in addressing global environmental and economic challenges, a comprehensive and systematic review of recent advancements in this field remains lacking. To address this gap, this paper synthesizes and analyzes academic literature published between 2021 and 2025, sourced from reputable databases including Scopus and Web of Science, while adhering to the PRISMA systematic review standards. It delineates core technologies employed in marine environmental monitoring, such as advanced sensor systems, robust data acquisition and transmission methods, and innovative data processing and analysis techniques. Furthermore, the study examines the architectural functionalities, data sharing mechanisms, and interoperability standards that underpin modern marine data platforms. The paper also addresses critical technical challenges encountered in deep-water monitoring operations, including equipment durability under extreme conditions, significant economic constraints, data management complexities, and emerging privacy and security concerns. Finally, future development trajectories are outlined, emphasizing the transformative potential of novel materials and artificial intelligence (AI) in enhancing deep-water monitoring capabilities, alongside the urgent need for strengthened global collaboration to improve data sharing protocols and management frameworks. Collectively, the continuous evolution

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ARTICLE INFO
Received: 30 June 2025 | Revised: 17 July 2025 | Accepted: 21 July 2025 | Published Online: 29 August 2025
DOI: https://doi.org/10.30564/jees.v7i8.10742

CITATION
Xie, B., Huang, B., Song, J., et al., 2025. Research Progress in Marine Environmental Monitoring Technology. Journal of Environmental & Earth Sciences. 7(8): 376–407. DOI: https://doi.org/10.30564/jees.v7i8.10742

of marine monitoring technologies promises to provide increasingly intelligent, integrated, and systematic support for global marine protection efforts and sustainable resource stewardship.
Keywords: Marine Environmental; Marine Monitoring; Sensor Technology; Underwater Platforms; Ocean Data; Underwater Communication

1. Introduction

With the acceleration of global climate change and marine resource development, the importance of marine environmental monitoring is becoming increasingly apparent [1,2]. The ocean is not only rich in minerals, energy, and biological resources, but also plays a key role in global climate regulation and ecosystem balance. However, the complexity and extremity of the marine environment (such as high pressure, low temperature, and weak light) pose many technical challenges for data collection and environmental monitoring [3]. Achieving high–precision, wide–coverage deep–water environmental monitoring is crucial for understanding the dynamics of deep–water ecosystems, assessing the environmental impact of marine resource development, and formulating effective marine protection policies.

Currently, marine environmental monitoring has gradually expanded from shallow water areas to deep water areas, with research priorities shifting from single–parameter monitoring to multi–parameter, long–term monitoring. Although numerous mature shallow water environmental monitoring technologies are available, the unique characteristics of the marine environment demand new technical requirements, such as high–pressure resistance, corrosion resistance, stable data transmission, and real–time processing. To address these challenges, researchers have proposed various solutions in recent years, including those based on advanced sensor technologies [4], unmanned underwater vehicles (UUVs) [5,6], underwater acoustic communication [7], satellite transmission, and sub–sea optical cables [8]. In addition, the widespread application of big data and artificial intelligence has significantly enhanced the data processing and analysis capabilities of environmental monitoring systems [9,10], facilitating the trend towards diversified and intelligent marine data platforms.

However, the further development of monitoring technology still faces numerous challenges. First, the marine environment imposes stringent physical performance requirements on monitoring equipment, such as long–term operational stability, monitoring accuracy, and transmission reliability. Second, the research, development, deployment, and maintenance of monitoring equipment are costly, particularly in terms of economic investment for continuous deep–sea monitoring, necessitating a balance between efficiency and cost. Additionally, the management and open sharing of environmental data remain underdeveloped. How to achieve cross–platform and cross-border data sharing while ensuring data security and privacy remains an urgent issue to be addressed.

Based on the above background, this paper first systematically reviews the core sensing technologies that underpin marine environmental monitoring (such as CTD, current meters, etc.), which serve as the foundation for acquiring environmental parameters; next, it explores the various platform technologies that host and deploy these sensors (such as moored buoys, seabed–based equipment, AUV/ROV, etc.), which determine the spatio–temporal coverage and sustainability of monitoring; It then analyzes the key data transmission technologies connecting underwater sensing nodes with shore–based/data centers, addressing the challenge of real–time or near–real–time transmission of massive monitoring data; subsequently, it comprehensively discusses the limitations and challenges faced by the current technological framework; finally, it outlines future innovation directions and trends in technology development based on application requirements and bottlenecks.

2. Materials and Methods

2.1. Selection Criteria

This review follows the PRISMA guidelines. The search focused on peer–reviewed publications related to marine environmental monitoring technology. To ensure the technical relevance, timeliness, and quality of the literature, the following screening criteria were adopted (**Table 1**). These criteria aim to ensure that the included literature focuses on innovations in deep–sea environmental monitoring technology and substantially supports the research objectives.

Table 1. Document Selection Criteria.

Dimensions of Selection	Specific Criteria
Time Range	2021–2025 Peer–reviewed literature
Thematic Relevance	Marine monitoring technology: CTD sensors, ocean current sensing (ADCP/fiber optic), underwater platforms (AUV/ROV/moored buoys), etc.
Literature Type	Priority given to journal articles; gray literature (e.g., company manuals) used only as supplementary technical parameters
Language	Documents are available in English

2.2. Screening Process and Basis

The key databases included Scopus and Web of Science. The search query combines Boolean operators and specific field keywords as shown in **Table 2**. The 2021–2025 timeframe was selected to capture the latest breakthroughs in deep–ocean monitoring technology (such as CTD, ADCP, and AUV platform integration) while considering the pace of technological iteration and relevant policy/standard development. Two rounds of screening will then be conducted: the initial screening stage will be based on titles/abstracts, with exclusion criteria including non–technical topics (purely economic/policy analysis) and non–in–situ technologies (such as satellite remote sensing only); the full–text review phase involves technical validation and assessment of the literature, with a focus on verifying field application tests of ocean monitoring equipment, ultimately retaining core literature that meets criteria for multi–parameter simultaneous monitoring, platform compatibility, and engineering standards. Data extraction focused on three dimensions: sensor performance, platform capabilities, and transmission efficiency. Gray literature (e.g., company manuals) was only used to supplement technical parameter details. This process enhanced the review's practical relevance through domain–specific standards and technology-oriented exclusion mechanisms, but was limited by language biases (excluding non–English literature) and the lack of standardized data formats across platforms.

Table 2. Keywords used for the search.

Databases	Query
Web of Science	(TS= (Marine monitoring) AND TS= (Conductivity, Temperature, Depth Sensors* OR CTD* OR Ocean current sensing technology* OR ADCP* OR Acoustic Doppler Current Profiler * OR Marine data transmission* OR Marine underwater buoy* OR Marine Platform Technology*)) NOT (SILOID=("PPRN"))
Scopus	(TITLE-ABS-KEY(marine monitoring) AND ("Conductivity Temperature Depth Sensor"OR"CTD"OR"Ocean current sensing technology" OR "ADCP" OR "Ocean data transmission" OR "Marine data transmission" OR "Marine underwater buoy" OR "Marine Platform Technology")) AND PUBYEAR > 2020 AND PUBYEAR < 2026

2.3. Results

Figure 1 illustrates the literature screening process based on the PRISMA method. After executing the predefined search queries in the Scopus and Web of Science databases, an initial total of 1123 articles were identified (Scopus: 229; WoS: 894). After deduplication, 1084 articles were retained. Subsequently, an initial screening based on titles/abstracts was conducted, excluding 678 articles, leaving 406 articles to proceed to the full-text review stage. During the full–text review and technical validation assessment, 183 non–in–situ technology articles (e.g., numerical models), 62 prototype articles without sea trials (e.g., unverified graphene sensors), and 21 purely theoretical articles were excluded. Ultimately, 118 articles meeting the screening criteria were retained, forming the literature foundation for this review study.

3. Marine environmental monitoring sensor technology

3.1. Conductivity, Temperature, Depth (CTD) Sensors

Ocean temperature, salinity, and depth observations are one of the fundamental components of modern ocean surveys. Since the 1960s, the CTD (Conductivity, Temperature, Depth) instrument has been widely used in ocean surveys, with its development progressing in tandem with advancements in science and technology. CTDs support various observation methods, including real-time measurements during ship–based surveys, stationary self–contained observations, and disposable probe measurements. They provide high–precision physical environmental parameters of the water column in the surveyed area in real time, making them one of the most widely used instruments in marine surveys today[11,12]. CTD (conductivity, temperature, and depth) provides chemical and physical parameters of the water column. These parameters are typically obtained using platforms such as unmanned aerial vehicles (UAVs), ocean survey vessels, underwater gliders, wave gliders, surface unmanned vehicles, and various types of buoys, and are analyzed to predict ocean behavior[13,14].

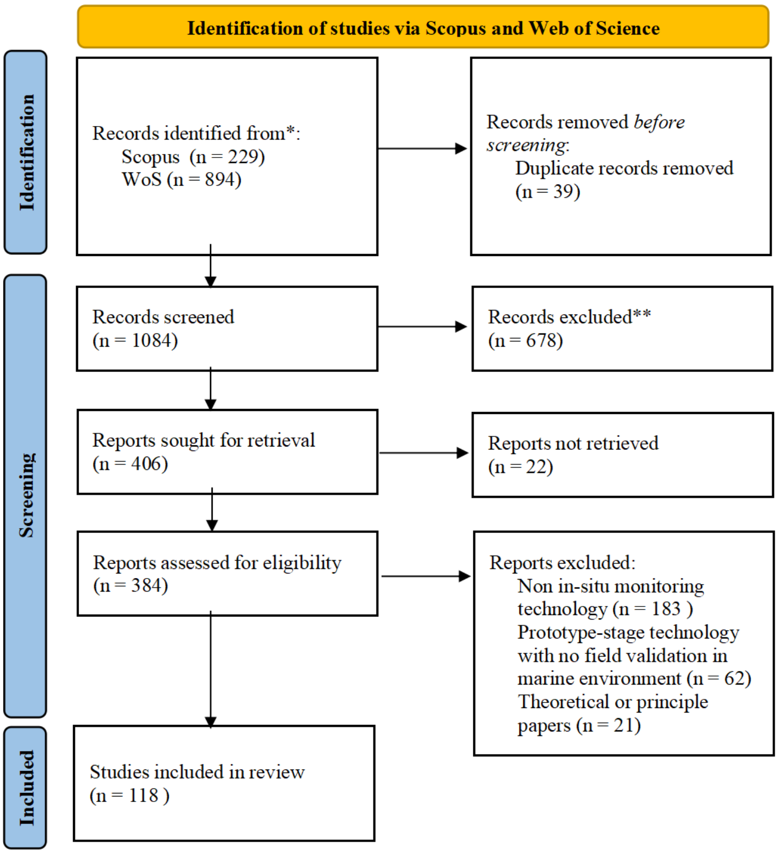

Figure 1. PRISMA Methodology Steps.

The development of CTD sensors can be primarily divided into three stages based on their technical characteristics: analog salinity compensation STD measurement technology, digital CTD measurement technology, and intelligent CTD measurement technology. Analog salinity compensation STD measurement technology originated in the 1960s. During this stage, salinity data was still obtained using traditional analog calculation methods[15]. There has been no substantial improvement in its fundamental design. The relationship between salinity, conductivity, temperature, and pressure is still simulated using a circuit[16], and the effects of temperature and pressure on salinity are compensated for using analog circuit compensation methods, as illustrated in **Figure 2**. In the 1970s, the era of digital CTD began, with the digitization of analog signals being the primary hallmark of temperature–salinity–depth sensing technology during this period. During this time, temperature–salinity–depth transmission signals were typically converted into binary code, recorded in memory, and then transmitted. The extraction of analog quantities gradually ceased to be used[17]. Since the 1990s, with the application of microprocessors in underwater probes, intelligent CTD sensor technology has begun to develop rapidly. The technical characteristics of this stage are primarily manifested in the following two aspects: underwater probes can perform zero and full–scale calibration and correction based on calibration constants stored in memory. This enables simultaneous digital measurement of sensor output signals, thereby improving measurement accuracy and reducing the workload associated with calibration and re–measurement. The bidirectional communication function between the water surface and underwater environments was achieved through the integration of microprocessors and general-purpose asynchronous transceiver technology [18,19].

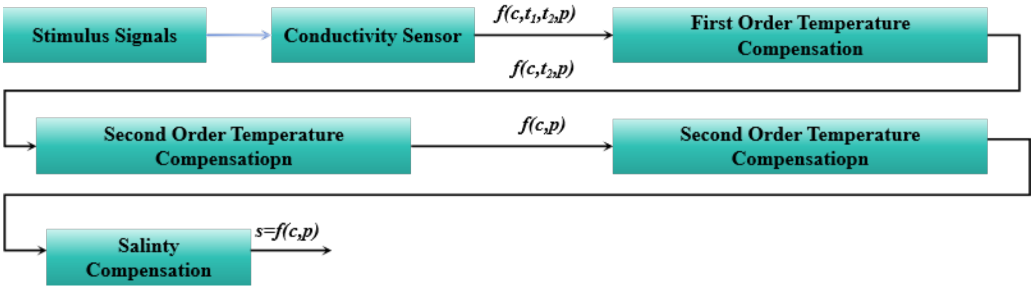

Figure 2. Schematic diagram of the compensation principle for STD salinity measurement.

The United States has long been the dominant player in the CTD industry, boasting a large number of well–known manufacturers and maintaining a leading position in terms of technological expertise. Companies such as SEABIRD, FSI, IO, and YSI are all world–renowned CTD manufacturers [20]. Among these, SEABIRD's SBE 911 Plus CTD stands out for its exceptional performance and has been designated as a standard measurement instrument by the International Oceanographic Commission [2]. The SBE 911 Plus CTD utilizes a three–electrode conductivity sensor, offering fast response times and high measurement accuracy. Its physical structure is shown in **Figure 3a**. The SBE 911 Plus CTD sensor adopts a modular design, consisting of a CTD unit, a deck unit, and a water sampler. It can be equipped with other types of sensors (such as dissolved oxygen sensors and pH sensors) as needed to perform multi–parameter measurements, enabling rapid and accurate acquisition of seawater CTD parameters. The deployment process can be roughly divided into equipment calibration, deployment, measurement, water sampling, and data processing steps. The larger electrode dimensions result in a relatively large overall volume. An external water pump is used to introduce seawater into the conductivity sensor to measure seawater conductivity, achieving high measurement accuracy through this method [21]. This CTD can operate in both self–contained and direct cable connection modes, and can measure underwater pressure down to 10,500 meters below the seabed, with a maximum sampling frequency of 24 Hz, making it highly suitable for measuring temperature, salinity, and depth in deep–sea environments. However, due to its weight and large size, it is only suitable for use in recent years. Countries around the world have intensified their efforts in the research and development of CTD sensors and breakthroughs in core technologies. To reduce the size of conductivity sensors and address issues such as contamination and polarization, many countries have begun researching four–electrode and even seven–electrode configurations. Significant progress has been made. The performance of the OCEAN SEVEN series CTD sensors produced by Italian company IDRONAUT [22] has been compared and tested by Swedish researchers [23,24], and is now on par with the 911Plus CTD. In addition, the CTD produced by German Sea & Sun Technology Company also demonstrates outstanding performance [25]. Both of these CTDs are designed based on seven–electrode conductivity sensors. Among them, the seven–electrode conductivity sensor of the OCEAN SEVEN 316S CTD produced by the Italian IDRONAUT Company, as shown in **Figure 3b**, features a simple structure and ease of disassembly and assembly. The 115M–type CTD produced by German Sea & Sun Technology also employs a seven–electrode design. In addition to the basic temperature, salinity, and depth measurements, this CTD integrates measurements of pH, dissolved oxygen, chlorophyll, and turbidity. Compared to the OCEAN SEVEN 316PlusCTD, it has a smaller volume and lighter weight, as shown in **Figure 3c**. Japanese CTD sensors have distinct advantages and a clear development direction, with self–contained design, compact size, portability, and low power consumption as their primary objectives. For example, the XCTD series products from Tsurumi–Seiki Company[26], as shown in **Figure 3d**, have a shallower measurement depth compared to other CTDs, with the XCTD–4N capable of measuring up to 1,850 m. However, its compact size and low power consumption allow deployment using a hand–held launcher, even on vessels lacking dedicated observation equipment. The portability of XCTDs also enables them to be carried on automated platforms such as drones or unmanned underwater vehicles (UUVs).

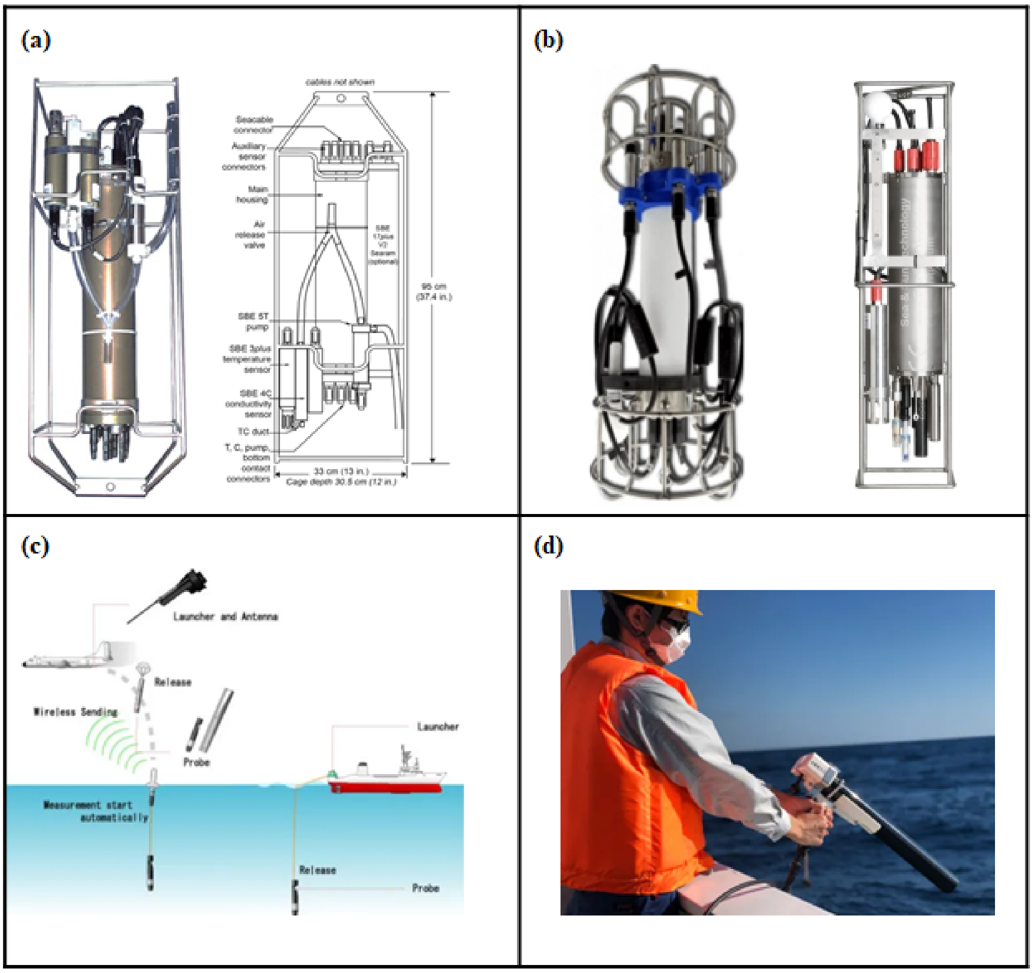

Figure 3. (**a**) SEABIRD three–electrode 911Plus CTD[2]; (**b**) IDRONAUT seven–electrode OCEANSEVEN320 CTD and Sea & Sun Technology 115M–type CTD[22]; (**c**) CTD measurement schematic diagram[25]; (**d**) Tsurumi–Seiki XCTD[26].

Currently, the development of CTD technology primarily focuses on comprehensive chemical and optical parameter measurements, with a greater emphasis on breakthroughs in high–capacity rapid storage technology[14]. The amount of data sampled per unit time has also significantly increased[27]. A typical example is the CTD profiler developed by ALEC Company, which uses self–contained power supply batteries that can be as small as size 5 or smaller. This not only effectively reduces weight to just a few dozen grams but also enables a standby time of up to several hundred days. However, its measurement accuracy is relatively low, positioning it in the lower–end market segment[28]. In addition, European maritime powers such as Norway, Italy, and the United Kingdom have consistently prioritized the development and innovation of CTD sensor technology. For example, Norway's AANDERAA Company has been dedicated to the research and development of current meters, CTD instruments, and related technologies.

The development of CTD sensors toward miniaturization, low power consumption, fast response, and low cost is an inevitable trend, and it is urgently necessary to overcome technical challenges from structural, material, and process perspectives. In recent years, various types of fiber optic sensors have garnered significant attention in marine environmental monitoring research due to their advantages, including compact structure, portability, simplicity of fabrication, low cost, high sensitivity, ease of integration and multiplexing, and the ability to achieve multi–parameter in–situ sensing[29–33]. The rapid development of fiber optic CTD sensor technology has opened new possibilities for marine environmental monitoring. Compared with traditional conductivity sensors, fiber optic sensors offer significant advantages in the marine environment, including robustness under extreme conditions such as high pressure and corrosion. Furthermore, their inherent electrical insulation makes them immune to electromagnetic interference. Additionally, fiber optic sensors have high sensitivity, enabling high–precision measurements of marine environmental parameters, which is of great significance for marine scientific research and resource development. The theoretical basis of fiber optic CTD sensors is the optical prism method[34], as shown in **Figure 4a**. The light beam emitted by the light source is transmitted through low–loss, low–noise, and corrosion–resistant optical fibers and passes through the seawater sample unit. The seawater sample unit, as shown in **Figure 4b**, can be divided into two parts: one part is filled with distilled water as a reference, and the other part is filled with seawater. The magnitude of the refraction angle (i.e., the position of the output light beam) is determined by the difference in refraction angles between the reference liquid and the measured liquid. By observing the position deviation of the light beam using a position detector (PSD), salinity measurement can be achieved. After calibration, the system can achieve a salinity measurement accuracy of 5‰. Based on this, the emergence of tunable optical fibers such as fiber gratings and photonic crystal fibers has further enhanced the sensitivity of fiber optic CTD sensors. Based on differences in the carrier of the sensing fiber and the sensing mechanism, all–fiber CTD sensors can be classified into fiber grating type and photonic crystal fiber type. Among these, fiber grating type CTD sensors, although relatively less sensitive, exhibit superior stability and environmental adaptability, and have gradually been applied in marine environmental monitoring engineering practices. Furthermore, due to their ease of large–scale integration and multiplexing, fiber optic grating sensors hold significant application potential in the study of marine environmental parameter sensing arrays and represent a currently viable technical approach. Although fiber optic sensing technology has made significant progress in marine environmental monitoring applications, demonstrating considerable value and advantages, further technological breakthroughs are still required to fully meet the demands of future marine monitoring network construction[35].

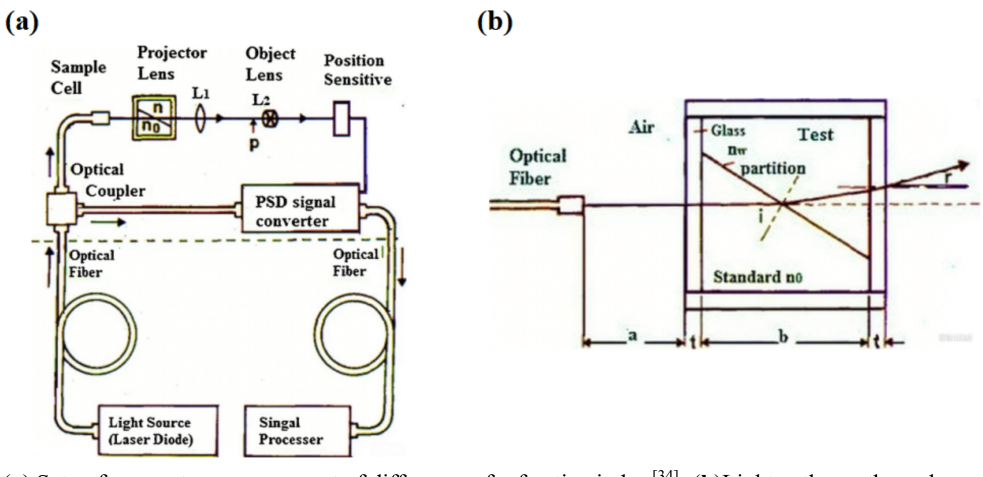

Figure 4. (**a**) Setup for remote. measurement of difference of refractive index[34]; (**b**)Light pathway through sample cell[34].

3.2. Ocean current sensing technology

In marine environmental monitoring systems, seawater flow velocity serves as a core dynamic parameter, not only reflecting physical processes such as wind force, water exchange capacity, and Coriolis force[36–39] but also providing critical data support for human activities such as marine transportation, military strategy, and resource development.

Accurate current velocity data enables optimized ship route planning and speed adjustments, reducing fuel consumption. It provides critical environmental intelligence for submarine navigation trajectory design and maritime defense deployment. Additionally, flow field analysis facilitates the precise location of natural fishing grounds, reducing operational costs and enhancing production efficiency. Therefore, high-precision flow velocity data serve not only as the scientific cornerstone for analyzing ocean dynamics but also as a critical technological component for ensuring national defense security and optimizing resource development efficiency.

Human understanding of ocean currents has deepened in tandem with ongoing advancements in detection methods and equipment. This evolution began with the earliest drifting object observation methods. A landmark event in 1905 was the invention of the Ekman current meter—the world's first mechanical ocean current meter—marking the dawn of an instrument-based era in ocean current detection technology. Subsequently, electromagnetic current meters emerged, offering significant improvements in flow velocity measurement accuracy and enabling three-dimensional flow measurement, thereby driving progress in the field. By the late 1960s, optical technology was introduced into the field of flow velocity and flow rate measurement. At the same time, fiber optic technology began to gain traction. LYLE et al. [40] developed a fiber–optic vortex flow meter; however, due to the limitations of fiber-optic technology at the time and the high cost of lasers, this solution failed to gain widespread adoption. A major technological breakthrough took place in the late 1970s to early 1980s with the development of the first acoustic Doppler current profiler (ADCP). This instrument achieved high-precision, non-contact three–dimensional current velocity profiling, marking the beginning of a rapid development period for ocean current detection instruments. Led by acoustic ocean current meters, detection devices began to specialize in different scales, depths, accuracy requirements, and environmental conditions. Today, ocean current detection instruments are deeply integrated with cutting-edge fields such as computers, satellite remote sensing [41] laser technology [42], and fiber optic sensing [43] advancing toward higher precision, intelligence, and integration, significantly accelerating the pace of human exploration and development of the oceans.

Based on their measurement principles, ocean current measurement instruments can primarily be categorized into six types: traditional mechanical, electromagnetic, acoustic Doppler, acoustic time-difference, fiber optic grating, and fiber optic interferometry ocean current meters.

Mechanical current meters (propeller-type current meters). These instruments utilize water flow to drive a rotor or propeller, calculating flow velocity based on its rotational speed and determining flow direction using a magnetic compass. As the earliest type of ocean current observation equipment developed by humans, it has made significant contributions to the history of ocean observation. Its advantages include a simple structure, low power consumption, and cost-effectiveness. However, its limitations are also significant: it can only obtain one-dimensional velocity information; the mechanical rotor has high inertia, making it prone to stopping at low flow rates, thus making it difficult to measure weak currents or rapid changes in turbulent flows; the contact–based measurement method disturbs the flow field, reducing accuracy; additionally, its moving parts are prone to corrosion and jamming in seawater environments, limiting reliability. Such instruments are typically deployed on fixed-point current measurement platforms, moored vessels, or buoys for stationary observations, and are suitable for nearshore, shallow water, and specific marine engineering scenarios. However, in deep–sea or long-term monitoring applications, they perform inferiorly compared to acoustic or optical instruments. Currently, mechanical current meters are primarily used in applications with lower accuracy requirements or as calibration tools for other types of current meters. There is still room for improvement in areas such as power consumption optimization, data acquisition accuracy, equipment reliability, and measurement real–time performance.

The SLC9–2 mechanical current meter developed by Ocean University of China (**Figure 5**) is a representative product of this type of instrument[44]. It achieves a flow velocity measurement accuracy of ±1.5% of full scale and a flow direction accuracy of ±4 degrees, demonstrating the current technical level of mechanical current meters in China. Research institutions with significant expertise in this field include: domestically, the National Institute of Ocean Technology, the Institute of Oceanology of the Chinese Academy of Sciences, and Ocean University of China; internationally, the Woods Hole Oceanographic Institution (WHOI) in the United States, the Scripps Institution of Oceanography (SIO) in the United States, Vale port Company in the United Kingdom, and Andera Company in Norway, among others.

Figure 5. (**a**) SLC9–2 mechanical ocean current meter of the Ocean University of China [44]; (**b**) HS–Engineers ISM–2001 electromagnetic ocean current meter [45].

Electromagnetic current meters are an important component of modern ocean observation systems, with their theoretical foundations traceable to Faraday's law of electromagnetic induction [46]—when a conductive medium (seawater) cuts through magnetic field lines, an induced electromotive force proportional to the flow velocity is generated between electrodes perpendicular to the flow direction. This non–contact measurement method makes it a critical device for upper ocean flux studies and deep–sea moored array deployment. Based on differences in magnetic field sources, electromagnetic current meters can be classified into geomagnetic–type and artificial magnetic–type: the former relies on the Earth's intrinsic magnetic field, featuring a simple structure but being significantly affected by geomagnetic anomalies; the latter generate a stable and controllable magnetic field via built–in excitation coils, increasing system complexity but significantly improving measurement stability, making them the mainstream solution. Compared to early mechanical propeller–type instruments, electromagnetic current meters represent a revolutionary advancement in three dimensions: first, they overcome the limitation of single–point velocity measurement, enabling simultaneous acquisition of two–dimensional vector data on flow direction and velocity; Second, it eliminates mechanical wear, biofouling, and inertial lag issues caused by moving parts; Third, it achieves instrument miniaturization and lightweight design, significantly enhancing deployment flexibility. Its velocity measurement accuracy can reach centimeter–level precision, with particularly outstanding robustness in strong shear flow fields [47].

However, the physical limits of electromagnetic technology are also well defined. When environmental electromagnetic noise exceeds the seawater–induced electromotive force by two orders of magnitude (e.g., near ship engines or submarine cable zones), the measurement signal is completely overwhelmed; High–frequency excitation requirements result in higher power consumption compared to mechanical current meters, limiting long–term observation capabilities; spectral analysis indicates that its transfer function approaches an ideal state in low–frequency macro–turbulence (5–20 Hz), but it is not suitable for larger turbulence intensities [48]. Operationally, the baseline voltage drift caused by changes in seawater conductivity requires daily calibration, and deep–sea high–pressure environments necessitate custom–made titanium alloy pressure chambers to protect electronic components [49]. These bottlenecks have led to a decline in electromagnetic current measurement technology research over the past decade [45,50].

When electromagnetic technology hits a development bottleneck, acoustic current measurement technology leverages its physical advantages to usher in a new era. The core principle of acoustic Doppler current profilers (ADCPs) lies in the Doppler frequency shift effect—the difference between the frequency of reflected sound waves and the emitted frequency is directly proportional to the relative velocity [37,51]. This acoustic remote sensing mechanism completely eliminates sensor interference from the flow field, enabling true non–contact measurement [52]. Acoustic Doppler current profilers (ADCPs) utilize wide–beam transmission and phased array reception technology to measure the entire velocity profile in a single measurement [53], offering high measurement efficiency and comprehensive data integrity. Acoustic Doppler velocity profilers (ADVs), on the other hand, focus on micro–scale turbulence studies with spatial resolution reaching the millimeter level [54]. The revolutionary contribution of these ocean current meters lies in upgrading discrete point measurements to three–dimensional field observations, and they can also measure through fixed–point and moving–platform methods, making them applicable to a wider range of marine environments. These devices face two core constraints: first, high manufacturing costs significantly raise the application threshold; second, physical mechanisms result in unavoidable detection blind spots. Velocity inversion is highly dependent on the scattering effects of suspended particles in the water column on acoustic waves, making it suitable only for nearshore areas with sufficient scattering particle concentrations. In regions such as polar ice caps or ultra–deep ocean basins where scattering particles are scarce, effective signal strength degrades to the noise background level [55], rendering measurements ineffective. Additionally, the spatiotemporal variability of marine environmental parameters significantly interferes with accuracy: coupled changes in seawater temperature and salinity indirectly introduce velocity errors through sound speed modulation; fluctuations in suspended particle concentrations alter acoustic wave attenuation characteristics; and multipath propagation effects induce phase interference noise, collectively forming a complex error source system.

Acoustic time difference current meters (also known as acoustic propagation time current meters) operate on the principle of measuring the time difference between the reverse and forward propagation of sound waves along a known fixed path length to calculate sea current velocity. This technology typically employs multiple transducer pairs to detect velocity components in different directions. These components are then vector–synthesized to obtain two–dimensional or three–dimensional velocity fields, with measurement depths that can be flexibly adjusted according to actual requirements [38,56]. If the system integrates compass information, it can also output ocean current vector data based on the Earth's coordinate system. The core of this technology lies in the high–precision measurement of sound propagation time between transducer pairs, with required accuracy levels typically reaching the nanosecond range.

Compared with acoustic Doppler current meters, acoustic time–difference current meters offer several distinct advantages. First, their design contains no mechanical moving parts, ensuring stable and reliable operation. They support both fixed–point observations and moving measurements and can obtain three–dimensional velocity information, typically achieving higher velocity measurement accuracy. Its operation is based on changes in the propagation speed of sound waves in a fluid medium, belonging to a transmissive measurement method. This means the measurement process does not depend on scattering particles in the water (such as particles or bubbles), is insensitive to bubble interference, and thus has no measurement blind zones. It is particularly suitable for flow velocity monitoring in complex environments such as turbulent flows, low–speed flows, pure water bodies, and wave–breaking zones [56]. Additionally, such devices typically enable long–range detection, giving them an advantage in applications requiring wide–area flow velocity monitoring, such as large ocean areas, rivers, and open channels. However, acoustic time–difference–of–flight current meters also have certain limitations. One major drawback is that when ocean currents pass through the transducer, they can cause minor water disturbances and wake effects, which may affect measurement results. A more significant limitation lies in the traditional time–difference method, which uses a transmitter–receiver transducer pair that requires alternating control of signal transmission and reception states, resulting in intermittent sampling over time. Under this sampling method, the propagation times of upstream and downstream sound waves are not measured simultaneously, leading to significant errors in scenarios with rapid instantaneous fluctuations in sea currents. This hinders true continuous real–time monitoring of sea currents, limiting temporal resolution.

Representative products include the MAVS–5 series from the U.S.–based NOBSKA Company (**Figure 5**), which has a velocity measurement range of approximately 0–3 m/s and an accuracy of up to 0.003 m/s. Internationally, major institutions engaged in the research and development of this technology include the Woods Hole Oceanographic Institution in the U.S., NOBSKA Company, FSI Company, and Sensate Company in Norway. Currently, commercialized products (such as 3D–ACM, 2D–ACM, and MAVS series) dominate the market (Figure 6). In contrast, China's research in this field is relatively weak. Although institutions such as Harbin Engineering University and the National Ocean Technology Center have conducted research on acoustic time difference current meters, no mature commercialized domestic products have been developed to date.

(a) (b)

Figure 6. (**a**) RDI Workhorse Monitor Series ADCP [57]. (**b**) NOBSKA MAVS series acoustic time difference current meter [58].

When acoustic technology encounters physical limitations and industrial barriers, fiber optic sensing opens up a new dimension for ocean current measurement [59]. Advances in fiber optic materials science, microfabrication processes, and grating manufacturing technologies have enabled continuous innovation in the design and performance of fiber optic flow velocity sensors based on various optical principles. These sensors, with their unique optical signal transmission mechanism, demonstrate significant advantages in detection sensitivity, spatial resolution, and long–distance interference–resistant transmission capabilities, gradually becoming an important development direction in the field of flow velocity measurement. From the perspective of core sensing mechanisms (Figure 7), fiber optic flow velocity sensing technology can be broadly categorized into two main types: fiber grating–based and interference–based. Although these two approaches follow distinct technical pathways, they share a common fundamental principle: to precisely monitor how fluid flow modulates light signals—manifested as changes in spectral characteristics or phase information—and to correlate these changes with flow velocity for calculation.

In the fiber Bragg grating (FBG) technology route, fiber Bragg gratings (FBGs) play a pivotal role. As the core sensitive element [60], FBGs operate by detecting changes in the reflected center wavelength caused by external fluid conditions, such as strain induced by flow velocity or temperature variations. Currently, based on the different physical effects caused by flow velocity, there are primarily two technical branches: the first is based on strain changes [61], where fluid forces (such as impact) cause deformation of the elastic structure attached to the FBG, resulting in a change in the grating period and subsequent wavelength drift; The second is based on temperature changes [62], utilizing the difference in cooling efficiency of specific heating regions (hot spots) caused by flow velocity, and indirectly measuring flow velocity by monitoring temperature changes (reflected as wavelength shifts). It is worth noting that applying thermal sensing to liquid flow velocity measurement (e.g., seawater) presents unique challenges. Compared to air, the high thermal capacity of liquids requires more efficient photothermal conversion mechanisms in design, which typically necessitates the use of high–thermal–absorption functional coatings or external auxiliary heating sources [63]. As shown in **Figure 8**, this is a typical design: FBG1 at the fiber core is covered with a high–thermal–conductivity material to form a hot–line region. After laser heating, its Bragg wavelength λ1 shifts to λ1*. As fluid flows through, heat dissipation occurs, causing λ1 to blue–shift to λ3. By demodulating this shift (λ3–λ1), the flow velocity can be calculated. Another FBG2 is specifically used for environmental temperature measurement and compensation. The direction for technical optimization is clearly evident. In 2017, LIU et al.[64] attempted to enhance the photothermal effect in the hot zone by using special Co^{2+}–doped multimode optical fibers. In 2020, NOVIKOVA et al.[64] significantly improved the photothermal conversion efficiency of the FBG array by coating it with silver–based adhesive, achieving a sensor sensitivity of 697 pm/(m/s) and compatibility with both gas and liquid flow rate measurements. Notably, flow direction detection capability has also been enhanced. In 2023, KLISHINA et al.[65] designed a novel sensor (**Figure 9**) by encapsulating two optical fibers with a tin–lead alloy (one multimode fiber to enhance light power and generate a cone–shaped heating zone, and another single–mode fiber containing three spatially distributed FBG arrays as the sensitive units), Experiments demonstrated that at low water flow rates of 0.02–0.05 m/s, the wavelength shift differences among the three gratings were sufficient to accurately distinguish flow direction, enabling simultaneous single–probe measurement of flow velocity and direction.

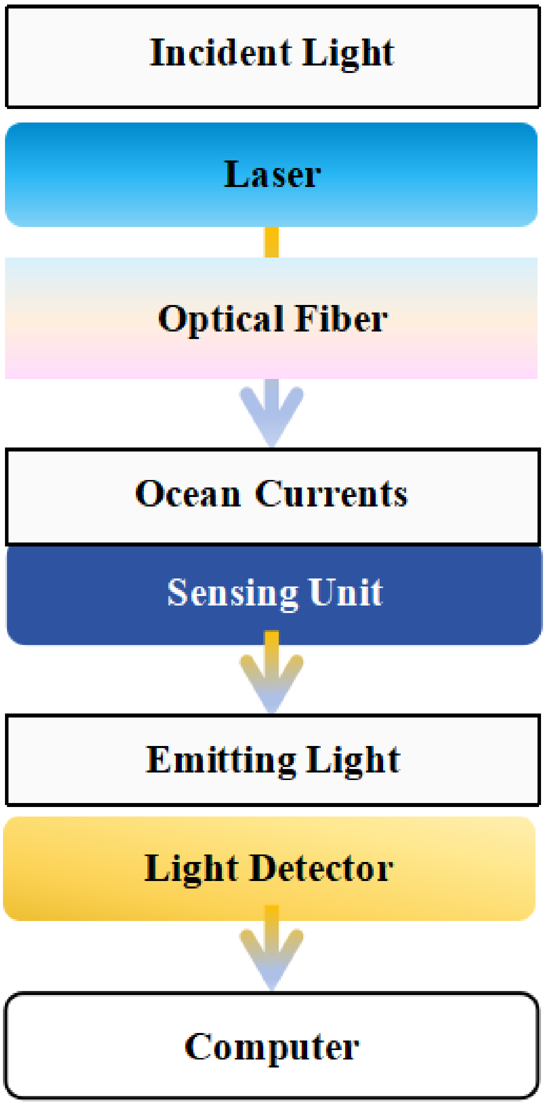

Figure 7. Fiber optic flow velocity sensing mechanism.

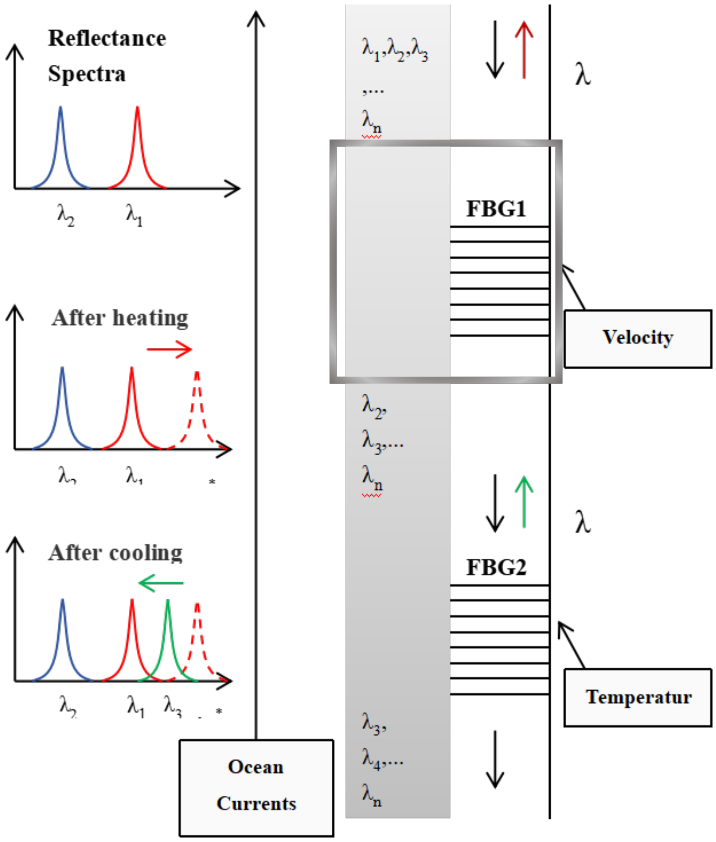

Figure 8. Principle of flow velocity measurement based on the hot wire method [65].

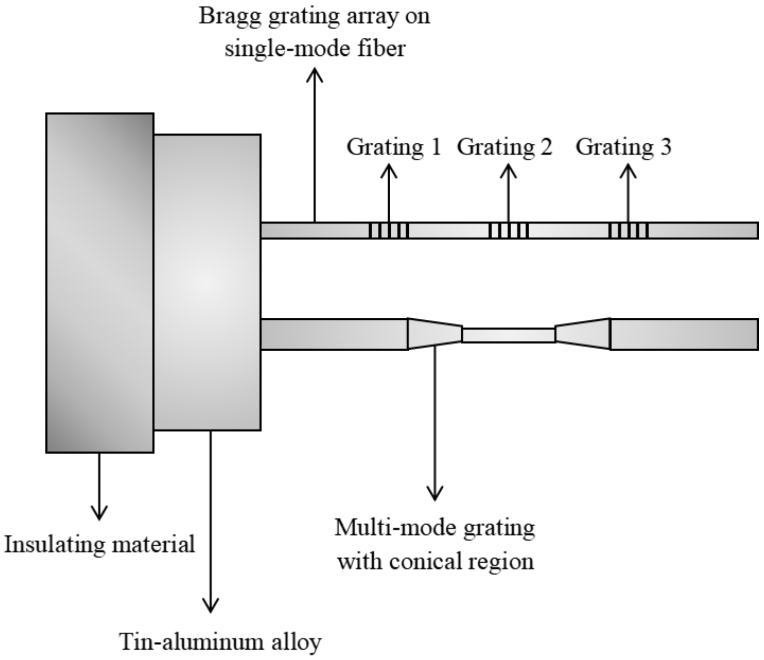

Figure 9. Schematic of the sensitive element of a flow sensor [65].

In addition to thermal sensing, the target-type structure is another important implementation form of fiber optic grating flow velocity measurement (**Figure 9**). The core principle involves converting fluid dynamics into measurable mechanical strain: the thrust generated by fluid impacting the target plate is transmitted through an intermediate force-transfer structure to a cantilever beam, causing it to deform. This deformation, in turn, stretches or compresses the fiber Bragg grating (FBG) attached to its surface, resulting in a shift in its central wavelength. By demodulating this wavelength shift and using a calibrated model, the flow velocity can be calculated. However, the wavelength shift corresponding to the minute strain caused by the cantilever beam's deformation often approaches the demodulation limit. To address this challenge and overcome the inherent temperature-strain cross-sensitivity issue of FBGs, a common approach is to symmetrically attach a pair of FBGs on both sides of the cantilever beam [66]. This configuration not only effectively amplifies the strain signal through differential measurement (one FBG is stretched and the other compressed when the beam bends) but also cleverly achieves temperature self-compensation (temperature changes affect the symmetrical gratings identically, and the effects can be canceled out after differential measurement).In 2023, DING et al. [67] designed a scheme integrating cladding fiber Bragg gratings into a cantilever beam structure composed of a spring and a circular target plate. Experimental results showed that the sensor's velocity response range was 0–87 mm/s, with a temperature sensitivity of only 9.5 pm/°C, and its spectral intensity varied minimally with temperature, indicating that temperature crosstalk was effectively suppressed. The performance of the entire sensor structure largely depends on the efficiency and accuracy of the force transmission mechanism. Research has focused on optimizing the target plate (shape, size), cantilever beam (material, length, thickness), and their connection methods to precisely control the sensor's range and sensitivity. For example, in 2016, LIU et al. [68] validated the feasibility of an "integrated" design that eliminates the traditional intermediate force-transmitting structure and directly uses the cantilever beam to fix the target plate as the sole force-receiving unit. This structure causes less interference with the flow field, has a more compact structure, and is easier to seal. However, complex mechanical structures often lead to error accumulation. In 2021, ZHANG et al. developed a system with flow direction adaptive monitoring and forward flow velocity measurement functions [69] (flow measurement range: 0.05–5 m/s), which introduced larger errors due to the use of multiple transmission mechanisms. On the other hand, in 2022, HOU et al. [70] integrated three structural optimization strategies—adding protrusions on both sides, combining rectangular beams, and increasing the thrust surface—to enhance the effective strain transmitted to the FBG (**Figure 10**). The experiments demonstrated that increasing the sensor target diameter and reducing the cantilever beam thickness significantly improved velocity sensitivity.

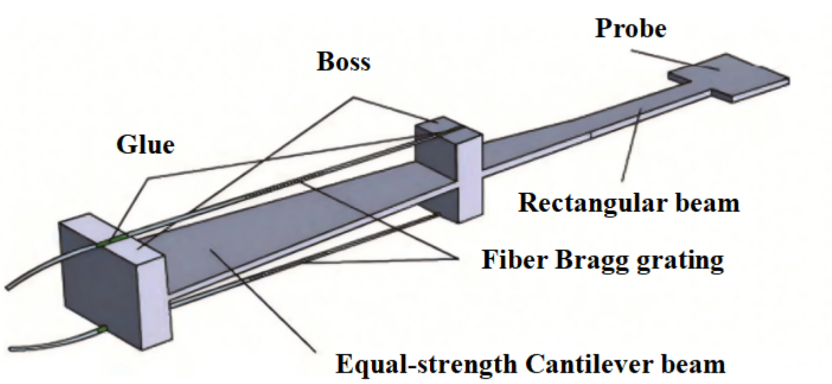

Figure 10. Schematic of the sensor structure [70].

One of the core advantages of fiber optic grating-based flow velocity sensors lies in the fact that flow velocity information is highly reliably encoded in wavelength changes. This means that measurement results are insensitive to interference factors such as fluctuations in light intensity, fiber optic connection losses, and changes in polarization state, thereby ensuring high measurement accuracy and long-term stability of results. However, its application also faces core challenges: the issue of FBG's cross-response to temperature and strain must be addressed. Additionally, the precision manufacturing process for high-quality fiber Bragg gratings is costly; simultaneously, achieving high-precision wavelength drift demodulation requires high-performance, high-resolution spectroscopic analysis equipment, which significantly increases measurement costs and, to some extent, limits the large-scale commercial application of this type of sensor. In terms of deployment, fiber Bragg grating-based current meters are highly suitable for profile measurements at different depths or multi-point distributed deployment at fixed locations, particularly for critical applications such as subsea pipelines and offshore platform structures that require long-term, real-time, and in-situ monitoring [71]. However, their typical requirements for complex on-site installation and calibration processes, as well as their sensitivity to dynamic environmental changes, make them less suitable for applications requiring frequent relocation, such as towed current measurement tasks.

The trend toward all-optical fiber systems in fiber optic sensing technology, coupled with the continuous advancement of high-power, high-coherence laser technology, has driven the development of interferometric fiber optic current meters [72]. The basic principle of this type of sensor is based on the optical interference of dual or multiple light beams [73]: when the sensing fiber optic arm undergoes a change in optical path length (ΔL) due to the influence of the flow field (such as thermal effects or mechanical stress), the phase difference (Δφ) of the interfered light or the interference fringe pattern changes accordingly. By precisely demodulating this optical phase information, the flow velocity can be inferred. Based on the specific interference structure, this type primarily includes three mature configurations: the Fabry-Pérot interferometer (FPI), the Mach-Zehnder interferometer (MZI), and the Michelson interferometer (MI).

The structure of the fiber optic FPI (**Figure 11**) typically involves depositing a thin film on the end face of the fiber optic or machining a small, sealed resonant cavity (Fabry-Pérot cavity) inside the fiber optic [74]. When the cavity length (L) or the refractive index (n) of the medium inside the cavity is modulated by the flow velocity field (e.g., thermal expansion causing changes in cavity length or flow velocity causing small fluctuations in refractive index), the resonant wavelength or phase of the interferometric light changes accordingly. FPIs have prominent advantages such as compact structure, no need for additional physical reference arms, and good stability [75,76], making them advantageous in microfluidic flow velocity analysis [75,76] and gas flow field sensing. Methods for constructing FP cavities are diverse, and ISLAM et al. [77] provided a systematic summary of these methods. Technological innovations continue to emerge: In 2016, ZHOU et al. [78] utilized a pair of FBGs etched into a single-mode optical fiber as mirrors to form an FP cavity, and fused a segment of cobalt-doped optical fiber between them as a thermosensitive element to enhance the thermal response of the cavity length to flow velocity; In 2019, COSTA et al. [79] proposed a flow sensor-like device for microfluidic measurements; another study involved fusing a short segment of multimode fiber with a gold-coated tip to one end of a single-mode fiber, utilizing the mode field transition from single-mode to multimode fiber and mode interference within the multimode fiber to introduce phase modulation. Interference fringe fineness (Finesse) is one of the key performance indicators for FPI, highly dependent on the reflectivity of the FP cavity mirror and the optical properties of the medium within the cavity. This characteristic is being utilized to develop high-performance flow sensors. In 2016, LIU et al. [80] designed a fiber optic vector velocity sensor based on a laser-heated silicon FPI array for turbulence detection (**Figure 12**). The core of this sensor utilizes the high flatness of silicon columns (as cavity mirrors) to form FP cavities. Experimental results demonstrate that the velocity response is linearly related to the heating laser power, and this structure achieves partial temperature self-compensation. In 2021, ZHANG et al. [81] proposed the concept of a hot-wire flowmeter by cascading FPI and FBG. This hybrid structure combines the spectral stability of FBG with the wide dynamic range of FPI, making it particularly suitable for low-flow measurements. By arranging multiple such sensors in an array, it can also be used for flow velocity direction measurement, demonstrating significant application potential in flow monitoring in the petroleum industry [82].

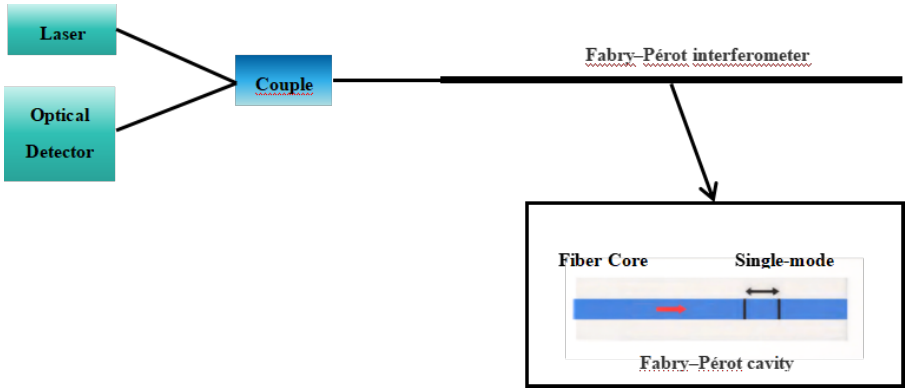

Figure 11. Basic structure of the Fabry-Perot fiber interferometer [74].

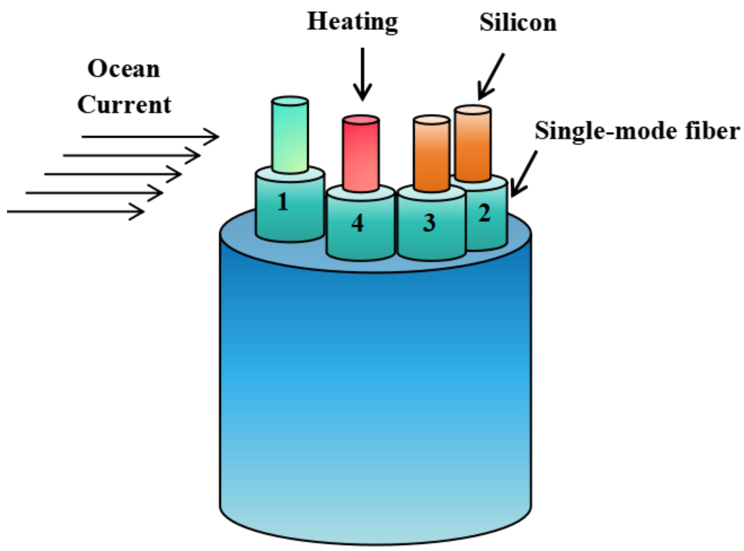

Figure 12. Schematic of the vector flow sensor head [80].

In contrast to FPI, the fiber-optic MZI is a double-beam interference structure whose classic configuration consists of two fiber couplers (the first splits the beam, the second combines it) connected to form two independent optical paths: the sensing arm is exposed to the flow field to be measured, while the reference arm is located in an undisturbed environment. When flow velocity acts on the sensing arm, causing a path length difference, the output spectra of the two light beams interfered at the second coupler exhibit characteristic shifts or intensity changes [83]. Fiber MI is theoretically consistent with MZI but belongs to a reflective structure: a single fiber coupler splits the light into two paths, which are reflected back after reaching the ends of two fibers coated with high-reflective films, and then meet again in the coupler to interfere. In most practical designs, the two reflective end faces are fixed after adjustment, with the sensing arm (the fiber itself) serving as the sensitive element. In this case, the phase modulation mechanism of MI and MZI is identical, with the primary distinction being whether the incident and received light signals are on the same side (MI on the same end, MZI on opposite ends). Representative research work includes: In 2008, YUAN et al. [84] achieved liquid flow velocity measurement with a dynamic range of 0–6 mm/s by coating one end of a dual-core optical fiber with a silver reflective surface and fusion-splicing a single-mode optical fiber at the other end to construct an MI. In 2021, HOU et al. [85] innovatively fabricated an all-fiber target-type flow sensor based on the MI principle using arc discharge fusion technology. The core of this sensor is a fiber "peanut-shaped" structure formed by electrofusion (serving as a coupling and beam splitter), where the incident light enters the core and cladding of the cantilever beam, is reflected by a spherical target, and then re-couples and interferes through the same peanut-shaped structure. The flow velocity measurement sensitivity reaches 1.30 nm/(cm/s), with a detection limit as low as 0.015 cm/s, demonstrating significant application potential in deep-sea fine flow fields and high-precision laboratory flow velocity measurements. In 2019, SUN et al.[86] proposed and fabricated a unique cascaded butterfly cone sensor based on an MZI, which uses fusion splicing to connect three segments of single-mode fiber into two butterfly-coupled structures. This sensor operates within a flow velocity range of 0.66–10.6 mm/s, offering advantages such as simple fabrication, low cost, and high sensitivity. However, its measurement error is approximately 8%, and accuracy degrades in scenarios with significant flow velocity fluctuations.

Compared to fiber optic grating-based devices, current meters based on the principle of interference typically exhibit superior performance in terms of response speed, spatial resolution, sensitivity, and measurement accuracy, especially in detecting weak and slow changes in flow velocity (such as in low turbulence zones and microscopic flow fields). This is due to the extremely high responsiveness of optical phase to minute physical changes. However, these sensors also have inherent limitations: since the measurement core relies on the coherent interference of light waves, phase noise and intensity noise from the laser light source significantly affect the signal-to-noise ratio, requiring extremely high stability of the light source, which inadvertently increases system costs and application barriers. For fiber-optic FPI sensors, precisely controlling the FP cavity dimensions and film thickness at the micrometer or even nanometer level is a critical manufacturing challenge. For fiber MZI and MI structures, increasing sensitivity often requires increasing the interference arm length, which not only increases the sensor size but also makes it more susceptible to additional environmental interference (such as vibration and temperature non-uniformity), sacrificing the long-term stability of the system. In addition, interference-based sensors also face the problem of Multiphysics (such as temperature, pressure, and strain) cross-sensitivity, which needs to be comprehensively considered in the design and signal processing.

Compared to fiber optic grating-based devices, interferometric current meters typically exhibit superior performance metrics, including response speed, spatial resolution, sensitivity, and measurement accuracy. This advantage is particularly pronounced in detecting subtle and gradual flow velocity changes, such as those occurring in low turbulence zones and microscopic flow fields. This is due to the extremely high responsiveness of optical phase to minute physical changes. However, these sensors also have inherent limitations: since the measurement core relies on the coherent interference of light waves, phase noise and intensity noise from the laser light source significantly affect the signal-to-noise ratio, requiring extremely high stability of the light source, which inadvertently increases system costs and application barriers. For fiber-optic FPI sensors, precisely controlling the FP cavity dimensions and film thickness at the micrometer or even nanometer level is a critical manufacturing challenge. For fiber MZI and MI structures, increasing sensitivity often requires increasing the interference arm length, which not only increases the sensor size but also makes it more susceptible to additional environmental interference (such as vibration and temperature non-uniformity), sacrificing the long-term stability of the system. In addition, interference-based sensors also face the problem of multiphysics (such as temperature, pressure, and strain) cross-sensitivity, which needs to be comprehensively considered in the design and signal processing. The current ocean current meter technology landscape exhibits a trend towards diversity and complementarity. In the future, ocean current field monitoring will continue to be centered on acoustic ocean current meters, combined with electromagnetic, fiber optic[87], and other types of equipment to provide multi-dimensional data support. Among traditional ocean current meter categories, mechanical devices have gradually phased out of mainstream applications. Electromagnetic sensors, with their non-invasive characteristics, primarily serve surface current velocity detection, while acoustic devices dominate due to their exceptional accuracy—among these, acoustic Doppler Ocean current meters achieve efficient profile measurements, and acoustic time-difference ocean current meters, with no measurement blind zones, resistance to bubble interference, and broad adaptability (turbulent/low-speed flows). However, currently available commercial ocean current meters generally suffer from high costs and insufficient sensitivity and accuracy under low-current conditions (**Table 3**). In contrast, fiber-optic current meters offer advantages such as high sensitivity, compact structure, low cost, resistance to electromagnetic interference, multiplexing, and remote control capabilities [88], providing a new path to overcome the technical limitations of traditional technologies.

Table 3. Comparison of Marine Environment Monitoring Sensor Technologies.

Sensor Type	Technical Principles	Advantages	Limitations
CTD sensor	Conductivity-temperature-depth	High precision, multi-parameter integration, modular design	Large volume, deep pressure drift (> 6000m)
Mechanical current meter	Rotary speed measurement	Simple structure, low power consumption, low cost	Only one-dimensional measurement, prone to clogging, weak flow failure
Electromagnetic current meter	Faraday's electromagnetic induction	Non-contact, anti-biofouling	Susceptible to electromagnetic interference, high power consumption, requires frequent calibration
Acoustic Doppler Current Profiler (ADCP)	Doppler shift	Non-contact, efficient profile monitoring	Polar/ultra-deep sea failure, high cost
Fiber optic current meter	Fiber optic grating/interference strain/thermal effect	Electromagnetic interference resistance, miniaturization, multi-parameter integration	Temperature-strain cross-sensitivity, high demodulation cost

Looking ahead, ocean current meter technology innovation will evolve along multiple dimensions: application scenarios will expand from marine exploration to river hydrological monitoring, pipeline flow measurement, and extreme environments (strong electromagnetic fields/high/low temperature regions), while specialized sensors will be developed for flammable and explosive fluids (e.g., crude oil), corrosive media, and biological microflows; Core performance will be continuously optimized, with a focus on enhancing measurement accuracy and spatial resolution to capture microscopic flow field structures, while expanding the measurement range to cover broader marine areas. Concurrently, the environmental adaptability and energy efficiency of the equipment will be strengthened; The system's intelligence and networking capabilities will be deepened through the integration of embedded artificial intelligence algorithms for real-time data processing and prediction. Combined with unmanned platforms, a remote monitoring network for deep-sea and offshore areas will be established, advancing toward multi-modal fusion by integrating acoustic, laser, and chemical sensors to simultaneously acquire multi-dimensional parameters such as flow velocity, temperature, salinity, and dissolved oxygen, thereby forming a comprehensive marine environmental sensing system.

The aforementioned advanced sensor technologies (such as high-precision CTDs, multi-principle current meters, fiber optic sensors, etc.) provide core sensing capabilities for obtaining marine environmental parameters. However, these sensors themselves require stable and reliable carriers for deployment, power supply, data collection, and preliminary processing, as well as to ensure their long-term stable operation in complex and harsh marine environments. Different types of monitoring tasks (such as large-scale surveys, fixed-point long-term observations, detailed profile measurements, and mobile flexible detection) have varying requirements for the carrier. Therefore, the development of marine environmental monitoring platform technology serves as the critical bridge connecting advanced sensors with practical marine observation applications. The next section will systematically explore the primary platform technologies supporting the operation of these sensors.

4. Marine Monitoring Platform Technology

As mentioned above, advanced sensors are the foundation for accurately sensing marine environmental parameters, but these sensors need to operate stably and reliably in complex and harsh marine environments. This requires an efficient and adaptable monitoring platform as a deployment carrier and operational guarantee.

A submerged buoy (also known as a mooring buoy) extends monitoring capabilities beyond those achievable with vessels and observation stations, enabling spatially and temporally continuous data collection [89]. It is the primary choice for monitoring tasks in harsh sea conditions, unmanned environments, and situations requiring long-term continuous monitoring in marine environments, where other monitoring methods are ineffective [90]. The moored buoy system consists of two parts: the surface component and the underwater component. The surface component includes an acoustic responder, an observation instrument, a beacon, and a mooring system; the underwater component comprises the buoy body, a wireless beacon receiver, an anchor system, an acoustic command transmitter/receiver, and a deployment/retrieval device. Compared to surface buoys, submerged buoys operate below the sea surface, minimizing the risk of damage from passing vessels or human interference, and thus offering higher safety and lower vulnerability. **Figure 13a** shows the PIES-type mooring for collecting marine seismic data, while **Figure 13b** illustrates the cNODE series mooring used for underwater construction positioning.

Figure 13. (**a**) Sonardyne PIES submerged buoy [91]; (**b**) Kongsberg's cNODE submerged buoy [92].

Due to the above advantages of submerged buoys, major maritime powers around the world have conducted research on submerged buoy platforms. Among them, foreign countries began their research earlier and achieved more advanced results. The United States initiated research on submerged buoy platforms in 1950 and began deploying submerged buoy observation systems in the Atlantic and Pacific Oceans in the 1960s to collect acoustic characteristics of target areas. The U.S. Navy started developing military submerged buoy systems in the 1970s, with the developed military submerged buoys featuring acoustic communication capabilities. Since then, dozens of submerged buoy systems have been deployed annually to monitor target areas. Around the 1980s, the United States began commercial services for submerged buoy systems, such as deploying systems to monitor the impact of ocean internal waves on drilling ship risers. The U.S.-developed N/SSQ-53DIFAR moored buoy system can detect target-emitted noise and estimate target azimuth using such noise, thereby enabling monitoring of alert zones [93,94]. European research on moored buoy technology lagged behind the U.S., with the UK deploying approximately 400 moored buoy systems in the 1970s for marine scientific research and regional surveillance; France deployed over 50 moored buoy systems to obtain the variation patterns of ocean currents, temperature, and other parameters with depth, and collaborated with Japan to deploy moored buoy systems near the equator to obtain parameters such as Pacific Ocean water temperature and current velocity [95]. The North Atlantic Treaty Organization deployed a series of moored buoys in the Mediterranean Sea to record various marine environmental parameters, transmitting data back to the base via underwater robots or high-speed communication technology. Russia has developed marine detection instruments capable of operating in the 1–150 kHz frequency band, enabling continuous monitoring and storage of marine environmental parameters for up to 18 days. China's first submerged buoy system was developed in 1982, capable of continuous operation for 105 days, and collected ocean current information at a water depth of 900 meters in a specific area of the South China Sea.

A seabed-based device is a bottom-mounted marine environmental monitoring system primarily used for continuous monitoring of marine hydrodynamic parameters such as suspended sediment, current velocity profiles, water temperature, tides, and waves. It plays a crucial role in marine three-dimensional monitoring networks due to its data reliability and minimal susceptibility to sea conditions. The system consists of a seabed-based platform, deployment and recovery system, and deck-mounted acoustic release unit. The seabed-mounted platform adopts a modular design, capable of accommodating various monitoring devices (such as ADCP, CTD, OBS, etc.) and can be flexibly configured to meet different monitoring requirements. The control system integrates data processing, equipment control, and communication with shore-based stations, ensuring the safe recovery of the equipment.

Internationally, leading maritime powers led by the United States have been researching and developing underwater observation networks since the late 20th century, utilizing submarine cables to achieve real-time continuous monitoring of ocean water layers and the atmosphere[96]. Currently, seabed-based technologies have been preliminarily industrialized, forming a complete production chain ranging from anti-trawling covers to acoustic release devices. Research institutions such as Oceanscience, MSI, SUB, and Flotel have developed various specialized platforms, including TECH[NICAP's TBM 1.76 (tetrahedral shape, equipped with ADCP, maximum operating depth of 120m, **Figure 14a**), MS's GP-TRBM and H-TRBM-65 (octagonal and spherical outer casings, primarily equipped with ADCP, **Figure 14b**), and Deep-Water BUOYANCY's AL series (operating depth up to 1,000 meters, **Figure 14c**).

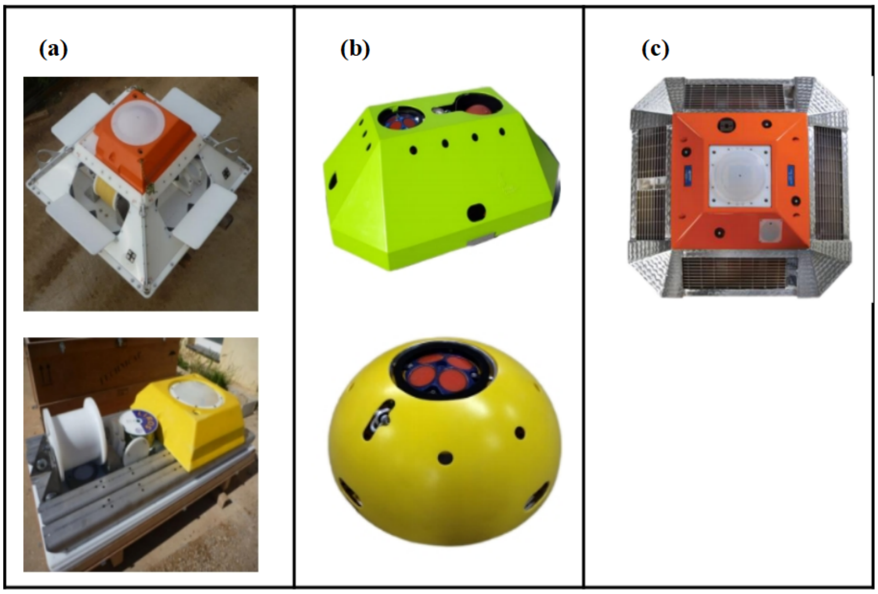

Figure 14. (**a**) TBM 1.76[97]; (**b**) GP-TRBM and H-TRBM-65[98]; (**c**) AL-200[99].

However, early seabed-based structure designs were structurally simplistic and suffered from several limitations: insufficient resistance to trawling and impact; vulnerability of exposed equipment to biofouling (not erosion); and compromised safety during deployment and retrieval. This is particularly problematic in shallow waters with frequent fishing and environmental operations, where it is difficult to ensure the long-term continuity and reliability of monitoring data. To address these issues, the current research and development focus is on optimizing the streamlined design of the outer casing and the use of new materials to enhance resistance to trawling and impact. Additionally, addressing the issues of equipment compatibility and interchangeability has become a key direction for further developing seabed-based systems.

Autonomous underwater robots, as highly autonomous and maneuverable underwater operation platforms, can dive deep into the ocean to perform tasks and are equipped with sensors or radars as tools for ocean monitoring[100]. Based on their connection method with the control end, underwater robots can be divided into two major categories: tethered and untethered[101,102]. Tethered underwater robots, also known as remotely operated vehicles (ROVs), are connected to a control unit via a cable, enabling remote operation and real-time data exchange[103]. However, due to the limitations of cable length, the operational range of ROVs is restricted. In contrast, untethered underwater robots, known as autonomous underwater vehicles (AUVs), possess higher autonomy and can operate over much larger areas than ROVs. However, data exchange typically occurs via wireless transmission or requires physical retrieval after the AUV returns to shore[104,105].

In the field of underwater robotics research, countries such as the United States, the United Kingdom, and Japan have taken an early lead, boasting substantial technical expertise. These nations established government-led research institutions at an early stage, including the Florida Atlantic University Advanced Marine Systems Laboratory in the United States, the Maritime Technology Center in the United Kingdom, and the Japan Agency for Marine-Earth Science and Technology in Japan. With technological advancements, underwater robots have gradually transitioned from military applications to civilian and commercial markets. Overseas commercial underwater robotics technology and its supporting industries have reached a relatively mature stage, particularly in the United States, where underwater robotics companies hold a leading global position. In recent years, driven by advancements in electronic technology, the manufacturing costs of underwater robots have further decreased. As a result, companies worldwide have begun to introduce cost-effective commercial underwater robot products, driving the growth of the underwater robotics market and providing strong support for new scientific research. The CURV series is a military underwater robot developed by the U.S. Navy Research Institute in the early 1960s (**Figure 15**).

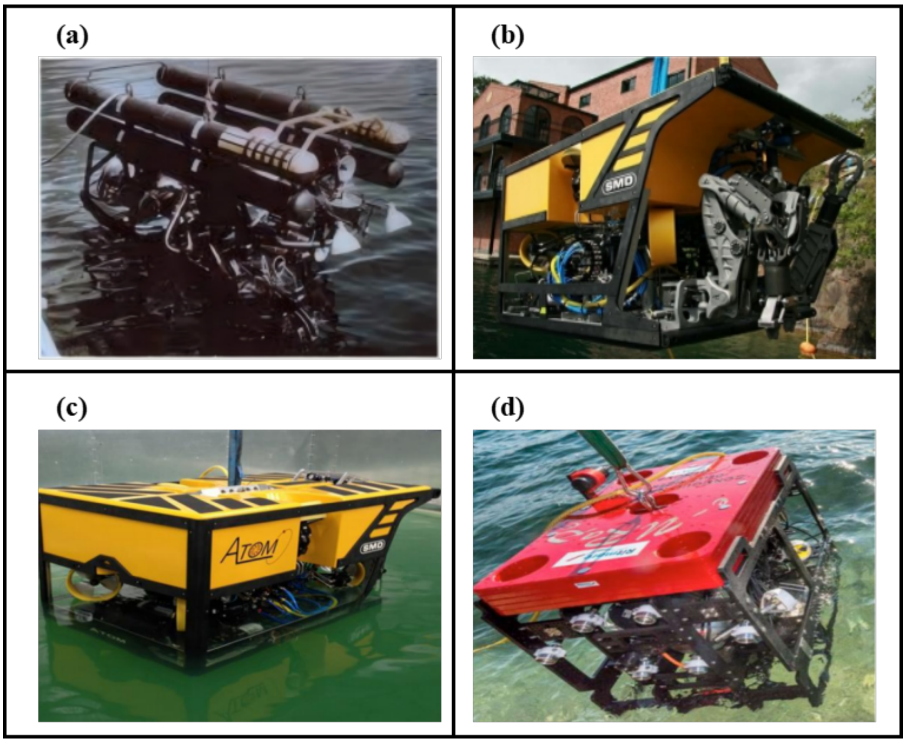

Figure 15. (**a**) CURV-I ROV[106]; (**b**) Quantum ROV[107]; (**c**) Atom ROV[108]; (**d**) e-URoPe ROV[109].

The first-generation model, the CURV-I underwater robot (**Figure 15a**), successfully recovered a lost hydrogen bomb in Spanish waters in 1966[110]. Building on this success, subsequent models, including the CURV-II and CURV-III, were developed, with the latest model being the CURV-21 underwater robot.

The UK is also a world leader in underwater robotics research. SMD manufactures a range of underwater robots for different working environments. Among them, ROVs such as Atom, Quasar, and Quantum are widely used in various industries (**Figure 15b,c**)[111].

e-URoPe is an underwater robot developed by the Italian CNR-ISSIA institute, combining the functions of a remotely operated vehicle (ROV) and an autonomous underwater vehicle (AUV). It can be operated remotely via a control system and also perform autonomous operations in a tetherless state[109]. Additionally, e-URoPe offers high assembly flexibility, with its frame structure, propulsion system layout, payload installation, and sensor/camera positions all adjustable according to operational requirements (**Figure 15d**). It can also easily integrate various tools, significantly enhancing the robot's operational flexibility. Currently, CNR-ISSIA is exploring the use of new materials and 3D printing technology to further reduce manufacturing costs and improve production efficiency.

Ocean One is an underwater robot jointly developed by Stanford University in the United States and King Abdullah University of Science and Technology in Saudi Arabia[112,113]. Its notable features include a highly anthropomorphic design and exceptional maneuverability. The underwater body is divided into an upper and lower section, with the lower section serving as an efficient propulsion unit and the upper section featuring an anthropomorphic structure with two humanoid robotic arms. Additionally, Ocean One is equipped with visual and tactile sensors, enabling it to perceive its environment. This structural design allows Ocean One to perform many tasks that were previously only possible for humans, such as underwater equipment installation and collaboration with divers. Currently, Ocean One has been applied in various fields, including marine archaeology, marine biology research, and underwater rescue operations.

Table 4 compares the core capabilities of mainstream monitoring platforms. Future platform designs need to balance coverage, endurance, and cost-effectiveness, for example, by optimizing data collection efficiency through AUV-buoy collaborative networks. From the perspective of marine monitoring platform technology, the current trend is moving toward higher levels of automation and intelligence. With the continuous advancement of sensor technology, data communication, and artificial intelligence algorithms, monitoring platforms are capable of real-time, continuous, and precise monitoring of the marine environment. For example, by equipping the platform with multi-parameter water quality sensors, acoustic detection devices, and biological sampling equipment, marine monitoring platforms can conduct long-term tracking of water temperature, salinity, dissolved oxygen, nutrient salts, marine species, and population. Additionally, the energy supply systems of these platforms are being optimized, with the adoption of renewable energy sources such as solar, wave, and tidal energy, enabling the platforms to operate stably and autonomously over extended periods without human intervention. In the future, marine monitoring platforms will increasingly integrate with satellite remote sensing technology to achieve large-scale, multi-layered monitoring of the marine environment, providing robust technical support for marine scientific research, resource development, and environmental protection.

Table 4. Comparison of technical capabilities of marine monitoring platforms.

Platform Type	Deployment Method	Capability	Range/Roverage	Cost	Typical Application
Anchor buoy	Fixed mooring	Long-term fixed-point multi-parameter (temperature, salinity, flow velocity)	Several months to several years (maintenance required)	High	Deep-sea long-term observation, military monitoring
Seabed-based equipment	Subsea fixed installation	High reliability, anti-trawling design, multi-sensor integration	Several years (self-contained power supply)	Mid-high	Offshore engineering monitoring
AUV	autonomous navigation	Large-scale mobile monitoring, three-dimensional profile measurement	Hours to days (battery limitations)	Extremely high (operation + maintenance)	Large-scale marine surveys and pipeline inspections
ROV	cable control operation	Real-time high-definition video, robotic arm operation	Limited by cable length	Extremely high	Underwater facility maintenance, archaeology, biological sampling

Various monitoring platforms (moored buoys, bottom-mounted devices, AUVs/ROVs) are equipped with advanced sensors that continuously generate massive amounts of marine environmental monitoring data. How to efficiently, reliably, and in real-time (or near real-time) transmit these valuable data from underwater, seabed, or mobile platforms to the surface, shore-based facilities, or data centers for processing, analysis, and application is a core component of building an effective marine monitoring network. The unique characteristics of the marine environment (such as the strong attenuation of radio signals by seawater) pose significant challenges for underwater data transmission. The next section will focus on key data transmission technologies and their research progress in marine environmental monitoring.

5. Marine data transmission technology

As mentioned above, communication technology in the field of marine environmental monitoring has long been constrained by unique environmental conditions, posing significant challenges to human activities in the ocean. Inspired by the tremendous success of IoT technology on land, extending IoT applications to underwater scenarios to create intelligent oceans represents a major future trend [114–118]. Underwater IoT connects underwater environments with related electronic devices (such as sensors, buoys, and unmanned underwater vehicles), playing a crucial role in climate change prediction, water quality monitoring, deep-sea exploration, and natural disaster warning [119–121]. However, due to the rapid attenuation of radio frequency signals in water, underwater communication primarily relies on acoustic devices. Consequently, underwater acoustic sensor networks form a critical component of underwater IoT. However, the slow propagation speed and limited bandwidth of sound waves result in high latency and error rates, making the improvement of underwater acoustic network performance and the extension of device lifespan core research directions.

In underwater IoT, data transmission mainly includes three stages: underwater to surface, surface to air, and air to underwater [122]. Sensors upload monitoring data (such as water temperature, pH, salinity, acoustic/seismic data, etc.) to buoys. The buoys then relay the data via unmanned aerial vehicles (UAVs/drones) to a control center ashore or aboard a ship for processing and analysis. If a task needs to be performed, the control center sends command data to the submersible via the buoys.

With the rapid development of the sixth-generation mobile communication system (6G), integrated air-ground-sea networks have emerged as one of the key application scenarios for 6G technology, offering the potential to enable a globally connected communication infrastructure. To enhance the monitoring and protection of marine resources and achieve seamless connectivity between devices and the environment, the marine Internet of Things (IoT) aims to establish a smart ocean ecosystem [121,123–126]. However, underwater sensors, unmanned underwater vehicles (UUVs), and buoys face significant challenges due to their limited power supply and the difficulty of replacing them, which poses severe challenges for optimizing communication quality and extending system lifespan. Based on the different stages of data transmission, research priorities can be summarized as follows.

Early underwater monitoring primarily relied on multi-hop routing methods for data transmission. Gopi et al. [127] designed an energy-optimized path hierarchical routing protocol based on a flying algorithm, effectively improving energy efficiency. Wahid et al. [128] selected relay nodes based on node depth and remaining energy, reducing energy consumption and latency. Wang et al. [129] proposed a multi-hop routing mechanism based on small cube partitions, optimizing cluster head rotation and relay node selection; however, the issue of uneven energy consumption remains unresolved.

To alleviate this problem, research has gradually introduced submersible-assisted collection methods. Han et al. [130] proposed a hierarchical data collection scheme that reduces sensor energy consumption by considering ocean current effects. Fang et al. [131] utilized an M/G/1 queueing model to improve data transmission reliability and timeliness. Although AUV-assisted data collection addresses some issues, the limited speed of AUVs makes this approach less suitable for time-critical applications. Gjanci et al. [132] proposed a path optimization method based on a data value decay model, but it is only applicable to sparse networks. Duan et al. [133] improved the remaining data value by optimizing paths, but a single UUV struggles to cover large areas.

UAVs have demonstrated significant advantages in disaster relief and remote area communications [5]. Duan et al. [134] optimized the uplink capacity of a UAV-assisted non-orthogonal multiple access communication system. Yang et al. [135] improved system energy efficiency through joint resource allocation and trajectory planning. However, existing studies have paid little attention to the energy consumption of buoys (such as signal transmission and reception) and have not sufficiently considered the energy balance between underwater and aerial links. Wang et al. [136] proposed a probabilistic model for drone-assisted cross-medium transmission, connecting underwater and aerial links. Ma et al.[137] optimized the network lifetime of drone-assisted networks through resource allocation, but failed to fully leverage the maneuverability of drones, limiting their potential for large-scale marine data collection.

The synchronization information and energy transmission characteristics of radio frequency signals make them promising for use in communication networks. Ju et al.[138] improved the total network throughput through time allocation optimization. Gautam et al.[139] proposed a resource allocation strategy for collaborative networks to optimize system speed. However, the inherent variability of the natural environment constrains the practical effectiveness and reliability of natural resource-based energy harvesting technologies[140].

Although significant progress has been made in marine environmental monitoring in terms of data transmission, many challenges remain, such as optimizing resource allocation in drone-assisted networks and improving data timeliness and system energy efficiency. Future research should focus on practical needs and explore innovative technical solutions to achieve the comprehensive development of smart oceans.

6. Limitation

Marine environmental monitoring has achieved transformative advancements through integrated "sky-space-land-sea" networks, enabling high-precision, multi-parameter oversight of marine ecosystems via technologies such as satellite remote sensing, autonomous underwater vehicles (AUVs), and AI-enhanced drone fleets. These innovations facilitate millimeter-scale salinity detection (± 0.005 PSU) and real-time pollution tracing, providing unprecedented scientific support for deep-sea resource exploitation and ecological conservation. To maximize these capabilities, policymakers must prioritize legally binding standards (e.g., ISO 21748 data protocols), adaptive funding mechanisms (e.g., Blue Carbon trading schemes), and sovereignty-sensitive data diplomacy under UNESCO/IOC frameworks—converting technological breakthroughs into anticipatory ocean governance.

However, three fundamental limitations constrain comprehensive system implementation:

1. Systemic Coverage and Technical Deficits

Persistent spatial and technological biases critically undermine data integrity. Monitoring networks disproportionately cover accessible coastal zones, neglecting > 90% of deep-sea trenches and polar regions where conventional instruments fail—acoustic Doppler current profilers (ADCPs) cease functioning in low-scatterer abyssal environments, creating critical hydrological voids. Concurrently, sensor degradation under extreme conditions (pressure-induced CTD drift beyond 6,000m, biofouling of fiber-optic cables) and unreliable low-flow detection (< 0.02 m/s) impede consistent data acquisition. Platform limitations further exacerbate gaps: moored buoys yield point measurements insufficient for system-scale analysis, while AUVs' energy constraints restrict operational ranges.

2. Energy and Data Transmission Bottlenecks

Operational sustainability faces critical energy barriers. Acoustic data transmission consumes >50% of system power with high latency, while titanium pressure housings escalate deployment costs by 8× compared to shallow-water operations. Renewable energy solutions remain ineffective in polar/low-sunlight regions, compounding energy deficits. Data governance challenges persist—fragmented CTD/ADCP output formats prevent interoperability, and military/commercial sensitivities restrict access to bathymetric datasets. AI-driven analytics face accessibility disparities due to computational resource demands, excluding developing nations from data utilization.

3. Economic and Validation Gaps

Economic and technological validation barriers hinder scalability. Deep-sea operations cost >$50,000/day, excluding resource-limited regions from monitoring initiatives. Maintenance at hadal depths costs 8× more than shallow-water interventions, forcing unsustainable coverage compromises. Crucially, laboratory breakthroughs often underperform in field deployments: fiber-optic sensors exhibit performance degradation under marine turbulence, while nanomaterials lack pressure-stability validation beyond 11,000m. Methodological constraints in research—primarily reliance on 2021–2025 English publications—overlook innovations in non-English literature and industry prototypes.

Synergistic solutions require policy-technology co-design: implement edge computing to alleviate 50% transmission energy burdens, accelerate ISO standardization for cross-platform interoperability, and establish tiered data-sharing frameworks balancing security with scientific needs. Only by addressing these materials, energetic, and governance constraints can we achieve truly intelligent and equitable marine monitoring and governance.

7. Conclusion

This review synthesizes recent advances and highlights significant breakthroughs in marine environmental monitoring technology: from the continuous innovation of high-precision CTD sensors to the development of intelligent observation networks using autonomous underwater vehicles (AUVs), and breakthroughs in technologies such as fiber optic sensing and acoustic Doppler current profilers (ADCPs), these advancements have significantly enhanced the ability to conduct multi-parameter, in-situ, long-term monitoring of deep-sea environments, thereby providing a robust scientific foundation for marine resource development and ecological conservation.

Looking ahead, future technological development will center on three key convergent trends:

1. Integration of smart materials and embedded AI to enhance equipment durability in extreme conditions (pressure, temperature, corrosion).
2. Air-space-sea architecture: Combine satellites, UAV relays, and underwater comms for near-real-time monitoring.
3. Global data governance: Establish shared standards/protocols to unify military, research, and industry data into trusted repositories.

Collectively, these trends outline the vision for a smart ocean network. This network will leverage: renewable energy-driven intelligent platform clusters (e.g., buoys, AUVs, underwater observatories); deep learning-powered data analytics; and secure data-sharing frameworks based on blockchain and other technologies. Ultimately, such a network aims to provide humanity with comprehensive capabilities to monitor, understand, and predict the state of the global marine environment across all regions, components, and temporal scales. This will not only reshape sustainable marine resource development models but also provide core technological support for addressing global climate change and marine biodiversity crises.

Author Contributions

All authors made significant contributions to this paper. Conceptualization, B.X. and B.H.; Investigation, B.X., J.S. and F.Z.; Validation, F.Z.; Writing—original draft preparation, B.X.; Writing—review and editing, B.H., J.S. and F.Z.; Visualization, B.X.; Supervision, B.H.; Project Administration, B.H. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data sharing is not applicable to this article, as there is no new data generated apart from the one listed in the article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review paper. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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