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Technical development of operational *in-situ* marine monitoring and research on its key generic technologies in China

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Abstract

In China, operational *in-situ* marine monitoring is the primary means of directly obtaining hydrological, meteorological, and oceanographic environmental parameters across sea areas, and it is essential for applications such as forecast of marine environment, prevention and mitigation of disaster, exploitation of marine resources, marine environmental protection, and management of transportation safety. In this paper, we summarise the composition, development courses, and present operational status of three systems of operational *in-situ* marine monitoring, namely coastal marine automated network station, ocean data buoy and voluntary observing ship measuring and reporting system. Additionally, we discuss the technical development in these *in-situ* systems and achievements in the key generic technologies along with future development trends.

Key words: marine observation technology, operational *in-situ* marine monitoring, C-MAN station, ocean data buoy, VOS measuring and reporting system, achievements in the key technologies, development trend

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1 Introduction

Marine observation is an activity to obtain data related to ocean specific parameters, phenomena and change processes in a certain space-time range with the help of technical means and instruments (Chen, 2019). Marine observation is the basis of ocean research, development and utilization. The development of marine observation technology plays an important role in enhancing the ability of marine environment monitoring, early warning and prediction of marine disasters, improving the ability of marine resources development, promoting the development of marine economy and science (Cai et al., 2007; Qi and Li, 2019). Marine observation instruments and equipment are the “eyes” for "watching the ocean", data source for “understanding the ocean”, the most direct and efficient ways for realizing large-scale and long-series time measurement of marine environment, and the pillar of building a three-dimensional real-time monitoring system of marine environment (Wang et al., 2014; Zhang, 2018). With the development of modern electronics, communication (Xu et al., 2021), computer technology and platform technology (buoy, ship, satellite, etc.) carrying a variety of marine sensing instruments, human beings can obtain marine information in a comprehensive, three-dimensional and real-time manner in the form of networking, and marine observation will continue to develop towards comprehensive intelligent sensing (Jiang and Pan, 2018).

Marine operational monitoring is a series of activities in which operational departments observe, judge, warn and control marine disasters and risks in the sea areas under their jurisdiction on the basis of marine observation. After 70 years of development in the marine monitoring technology, especially the rapid development in recent 30 years, a combination of national three-dimensional marine monitoring networks has been established in China and is being used in operational monitoring (Chen and Lei, 2019; Wang, 2017; Yi,1993; Zhu,1992). Presently, the combination includes five components, namely coastal marine automated network (C-MAN) (Han, 2003; Wang et al., 2019), ocean data buoy network (Chu et al., 2001; Dai et al., 2014; Li et al., 2014, 2008; Liu et al., 2019; Ren et al., 2011; Wang, 2013), voluntary observing ship (VOS) measuring and reporting system network (Dong and Zhang, 2016; Liu, 2009), shore-based radar network (Wang et al., 2012; Wu et al., 2015; Huang et al., 2020), and ocean satellite remote sensing network (Jiang et al., 2016, 2019; Lin et al., 2019; Pan and Gong, 2011). These five components for monitoring various real- and non-real-time elements on a daily

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basis are essential in several fields, including marine environmental forecast, early disaster warning, marine economy development, marine exploitation and conservation, as well as scientific study.

Three of these five networks, namely C-MAN, ocean data buoy network, and VOS measuring and reporting system network, have many operational *in-situ* marine monitoring instruments and have demonstrated advantages in terms of scale and maturity. What these three monitoring networks have in common is that they are all direct and real-time observation. Although the technical challenge is great, the continuously changing marine data obtained can better grasp the marine characteristics. The difference is that the C-MAN and ocean data buoy network are fixed, while the VOS measuring and reporting system network is mobile. They give full play to their strengths and complement each other. This paper focuses on elaborating the technical development and application status of the aforementioned three monitoring networks.

2 The role and current status of operational *in-situ* marine monitoring

2.1 *C-MAN stations: their role in national marine monitoring and current operation status*

2.1.1 *Role of C-MAN stations in operational monitoring*

C-MAN stations refer to observation facilities built on coastal shore-based sites, uninhabited islands, or offshore platforms; these sites serve as carriers and supports for automatic observation instruments. One of the main tasks of these sites is to collect time series of marine environment variables such as hydrology, meteorology, ecology, and water quality parameters in coastal areas, where economic activities are most concentrated, in addition to processing the obtained data. Thus, the stations provide fundamental data that reflect the basic characteristics and the variation patterns of marine environment in the observed waters; this information provides the foundation for environmental forecasting, engineering construction, and long-term exploitation and preservation of resources in coastal and continental shelf waters.

2.1.2 *Components and technical development of C-MAN stations*

A C-MAN station has five major components, namely sensor module, data acquisition unit, power module, communication module, and supervisory computer processing software (Zhang, 2000, 2001; Zhu et al., 2002).

Typically, a station observes 24 environmental parameters; of these, ① 5 hydrological parameters, such as tides, waves, current, temperature and salinity of surface water; ② 9 meteorological parameters, covering wind speed, wind direction, air pressure, air temperature, relative humidity, precipitation, visibility, light exposure, and height of clouds; and ③ 10 ecological parameters concerning the water quality in terms of pH value, redox potential, dissolved oxygen, chlorophyll, optical transmissivity, turbidity, ammonia nitrogen, nitrate nitrogen, total nitrogen, and total phosphorus.

Major steps in the technical development of a station system include: ① design to ensure robust systems that are reliable and stable in an oceanic salty spray environment; ② adaptable hardware systems of oceanic stations based on the self-adaptive technology; ③ adaptable hardware systems of oceanic stations based on component programming. Achievements in the above key technologies will better meet and ensure the observation operation of C-MAN stations, island automatic stations, offshore platform automatic stations and other stations.

2.1.3 *Development and current operational status of C-MAN stations*

The research of coastal marine observing station technology in China began in the 1950s. It is one of the earliest operational observation means of marine environment monitoring in China. For a long time, until the 1990s, it was a parallel operation stage of manual observation and semi-automatic observation. Most stations had outdated instruments and equipment, outmoded observation methods and low automation level. Coastal marine observing station was mainly manual. Before 1990, the total number of C-MAN stations accounted for only about 5% of the total number of coastal marine observing stations within China's State Oceanic Administration (Zhu, 1992).

The development of C-MAN station began in the 1990s. In view of the backward situation of less automatic observation technology and large manual observation workload of coastal marine stations in China at that time, the research on automated observation system for coastal marine stations was carried out in 1990s, the multiparameter modular technology of automated system for coastal marine observing stations was developed and manufactured (Zhang, 2000). This system was located in the South China Sea; since then, it has been providing technological support and assurance for the national coastal marine automated monitoring of the marine environment. By 2000, with the development of modern electronics, computer technology, automation technology and network communication technology, China had mastered the technology of C-MAN station, so that the proportion of the total number of automated stations in the total number of coastal marine observing stations in China rose to more than 50%, and the automatic observation equipment accounted for more than 80% of the total number of coastal marine observing stations. In the past two decades, with advancement of technology, the automatic system of coastal marine observing station products has evolved from the first to subsequent generations. Currently, the C-MAN station operates at a high degree of automation, with stable and reliable performance; moreover, its flexible configuration has been designed to adapt the usage in all weather conditions, covering hydrological, meteorological, and water ecological parameters. The data obtained by C-MAN stations are managed and queried through the data management and dynamic release system to realize the real-time sharing of observation data of multiple stations, which is of great positive significance to the early warning and prediction of marine environment (Qin et al., 2010).

China's C-MAN stations cover from Dandong, Liaoning in the north to the districts of Xisha and Nansha Islands in the south. C-MAN stations are located along the coast and other observing platforms on uninhabited islands, ports, wharves, and sea, as shown in Fig. 1. About 450 operational C-MAN stations are used for marine environment monitoring in China (Peng, 2022) by the dispatched oceanic agencies of Ministry of Natural Resources of the People's Republic of China, China Meteorological Administration, coastal provincial and municipal oceanic bureau, ports, docks, and marine science bases.

2.2 *Ocean data buoys and their role in national marine monitoring and current operation status*

2.2.1 *Role of ocean data buoy in operational monitoring*

Ocean data buoy usually refers to anchored buoy, which is an

Fig. 1. Coastal marine automated network stations.

unattended special instrument for fixed-point, automatic, long-term and continuous observation of hydrological and meteorological parameters in a specific sea area and sending observation data regularly. Along with scientific and technological advances and in response to the need of oceanic exploitation, ocean data buoy was developed to automatically monitor various oceanic parameters of hydrology and meteorology at fixed points in a whole-day, real-time, and continuous manner. Presently, it has become one of the main means of marine monitoring in wide expanses of offshore waters. In marine environmental monitoring and forecast, the buoy is mainly used for real-time monitoring of natural disasters, such as typhoons, tsunamis, storm surges, eutrophication, and red tides, in addition to the security of the marine environment that makes it an equipment of primary importance in the three-dimensional marine environment monitoring network.

Ocean data buoy is playing an increasingly important role in marine dynamic environment monitoring, marine pollution monitoring, authenticity verification of satellite remote sensing data (Chen et al., 2021), etc. Ocean data buoy network operates with a large monitoring coverage and is not susceptible to restrictions posed by natural conditions, and thus, it can obtain observation data even in severe marine environments (Shi et al., 2021). Since it became operational, this network will greatly improved China's capability of marine disaster forecasting and early warning, which has effectively promoted the development of the China's emergency marine disaster management system. The establishment and regular operation of the data buoy network are crucial for China's marine environmental forecast, early warning for disaster prevention and mitigation, marine exploitation and conservation, and marine scientific research.

2.2.2 *Components and technical development of the ocean data buoy*

The structure of ocean data buoy mainly consists of the buoy, moorings, and subsystems of data collection and control, communication, power supply, and sensors; in its entirety, the system ensures reliable operation of the buoy in an oceanic environment and measures, processes, and transmits various parameters of marine environmental data.

China has developed the first H23 buoy prototype since 1966. In 1978, China developed the first 10 m diameter disc large buoy (HFB-1). Focusing on the construction of China's ocean data buoy network, the stability and reliability of buoy long-term operation have been gradually solved from the key technologies such as harsh environment adaptability design, satellite communication, deep-sea mooring, data acquisition and control, the stability and reliability of domestic buoys have been greatly improved. The Institute of Oceanographic Instrumentation, Shandong Academy of Sciences, is one of the primary developer of ocean data buoy, in particular, it is the cradle of the 10 m disc ocean data buoy. With the support of National Scientific and Technological Projects, National High-Tech R&D Program (863 Program) and National Key R&D Program, from 1986 to now, the development of buoy technology in China has experienced key technology breakthrough, reliability improvement, equipment standardization and finalization, instrument sinicization (Bu and Liu, 2003; Li et al., 2004, 2012; Wang, 1998; Wang and Li, 2019; Yuan and Wang, 2002; Zhang, 1998; Zhao and Zhu, 2004). A buoy technology research, operational management, engineering use and technical support system has been established, which has fully met the needs of long-term operational monitoring in China's offshore waters and reached the international advanced level (Li et al., 2015).

Over the past 20 years, the following three major achievements have occurred in the technical innovation of the ocean data buoy:

(1) Developments in the key technology of buoy sensor

In response to the demand in refined marine environmental monitoring methods, various methods such as ozone digestion spectrophotometry, tetrahedron three-dimensional wind field acoustics measurement, and digital accelerometer wave direction measurement have been invented. In addition, new types of buoy sensors have been invented to ensure stable and accurate measurement of ecological parameters under high degrees of humidity, salinity, and turbidity. The aforementioned developments have significantly upgraded the comprehensive monitoring performance of the buoy.

(2) Development and innovation of a series of key buoy technologies

To address problems concerning the reliability and environmental adaptability of buoys, buoy with a complex system was proposed, and innovations such as control by dual controllers in parallel operation, hydrodynamic modelling, simulation of deep-water mooring systems, and mechanical connection of buoy's individual modules were introduced. Technical difficulties in resisting severe winds and waves in the ocean, safeguarding reliability, mooring at the deep sea, and developing assembled buoys have been overcome. These achievements have significantly reduced the average failure rate and tripled the time for reliable in-place operation of the buoy.

(3) Construction of the technical system of ocean data buoy and development of series buoy products

To meet different marine monitoring needs, serialized discus buoys with diameters of 15 m, 10 m, 6 m, 3 m, 2.4 m, and 1.5 m were developed. Functions of these buoys evolved from only regular operation to special purpose as their operation environment changed from dynamic to comprehensive (such as ecological environment) and their monitoring parameters increased from less than 10 to more than 20. Applications range from offshore to extreme environmental monitoring such as open sea and polar regions (Chen et al., 2020). Today, standards of buoys have been established to lead the technical development of buoys in China.

2.2.3 *Development and current operational status of the ocean data buoy network*

In 1987, the State Oceanic Administration laid the plan for ocean data buoy network, in which only 12 buoy stations had to be deployed in the Yellow Sea, East China Sea and South China Sea in the 1990s. After more than 30 years of development, China manages more than 100 operational moored buoy stations that are used by the State Oceanic Administration and China Meteorological Administration (Gan et al., 2019; Wang et al., 2016; Wang, 2017; Zhou et al., 2019; Peng, 2022). Most of the operational buoys in China are 10 m diameter disk mooring buoys. Now China has become the marine country with the largest number of 10 m buoys in the world. Considering other ocean users, the total number of buoys in use is approximately 200 (Peng, 2022).

According to the size of buoy hull, buoys are generally divided into large, medium and small. Based on buoy function, marine buoys can be categorised as meteorology buoy, water quality buoy, wave buoy, comprehensive monitoring buoy, and so on; based on buoy structural style, they can be classified as disc-shaped, pillar-shaped, loop-shaped, and sphere-shaped buoys. In terms of numbers in use and degree of technical reliability, anchored disc-shaped buoy is the most commonly employed. Serialized ocean data buoys are shown in Fig. 2.

The dispatched oceanic agencies under Ministry of Natural Resources of the People's Republic of China, relevant agencies under China Meteorological Administration and coastal provinces meteorological administration receive tens of thousands sets of monitoring data of environmental elements (such as marine meteorology, hydrology, and ecology) from the buoy network. It can be seen that the buoy network has played a very important role in achieving realtime monitoring and data accumulation of China's offshore marine environment.

2.3 *VOS measuring and reporting system: its role in national marine monitoring and current operation status*

2.3.1 *Role of VOS measuring and reporting system*

As an important part of the national marine monitoring system, the VOS measuring and reporting system is mainly used to collect various marine hydrological and meteorological data on the shipping routes of ships to realise marine monitoring on short-, medium-, and long-range voyage routes. The development of VOS measuring and reporting system can fill the gap of China's real-time monitoring capability in open seas; the valuable data thus obtained are of significance for marine weather forecast, marine scientific research, in addition to safety in maritime traffic, transportation, fishery and aquaculture, and at ports and terminals.

2.3.2 *Components and technical development of VOS measuring and reporting system*

Generally, the network of VOS measuring and reporting system comprises automatic hydrometeorological monitoring and forecasting instruments, a monitoring station, as well as an information management centre (Liang et al., 2008; Wang et al., 2011; Zhou et al., 2011).

VOS measuring and reporting system is installed on ship to collect, process, display, store, and transmit on-site hydrometeorological information. In addition, it receives and displays information about weather forecasts, wave warnings, and forecast typhoon paths.

The information management centre, as the operation management hub of the automatic hydrometeorological monitoring and forecasting instrument of the VOS, receives the monitoring data from the instrument via the Beidou Navigation Satellite System and delivers the forecast or other information via broadcast or point-to-point unicast. The centre is responsible for distributing data to units that are in joint development or cooperation; it also reports the monitoring data to the forecast centre along the administrative hierarchy. Additionally, it receives forecast products from the forecasting department and sends this data in a coded form to the monitoring stations or to the automatic hydrometeorological monitoring and forecasting instruments under its management.

In China, the application of the VOS measuring and reporting system began in the 1950s. At that time, simple meteorological observation was mainly carried out by means of fishing boats and manual visual observation, and the observation results were transmitted by telegram. In the 1970s, the VOS measuring and reporting system began to expand observation parameters, increase instrument observation and compile observation specifications. Since the 1990s, with the development of marine technology and the research of automatic equipment, marine automat-

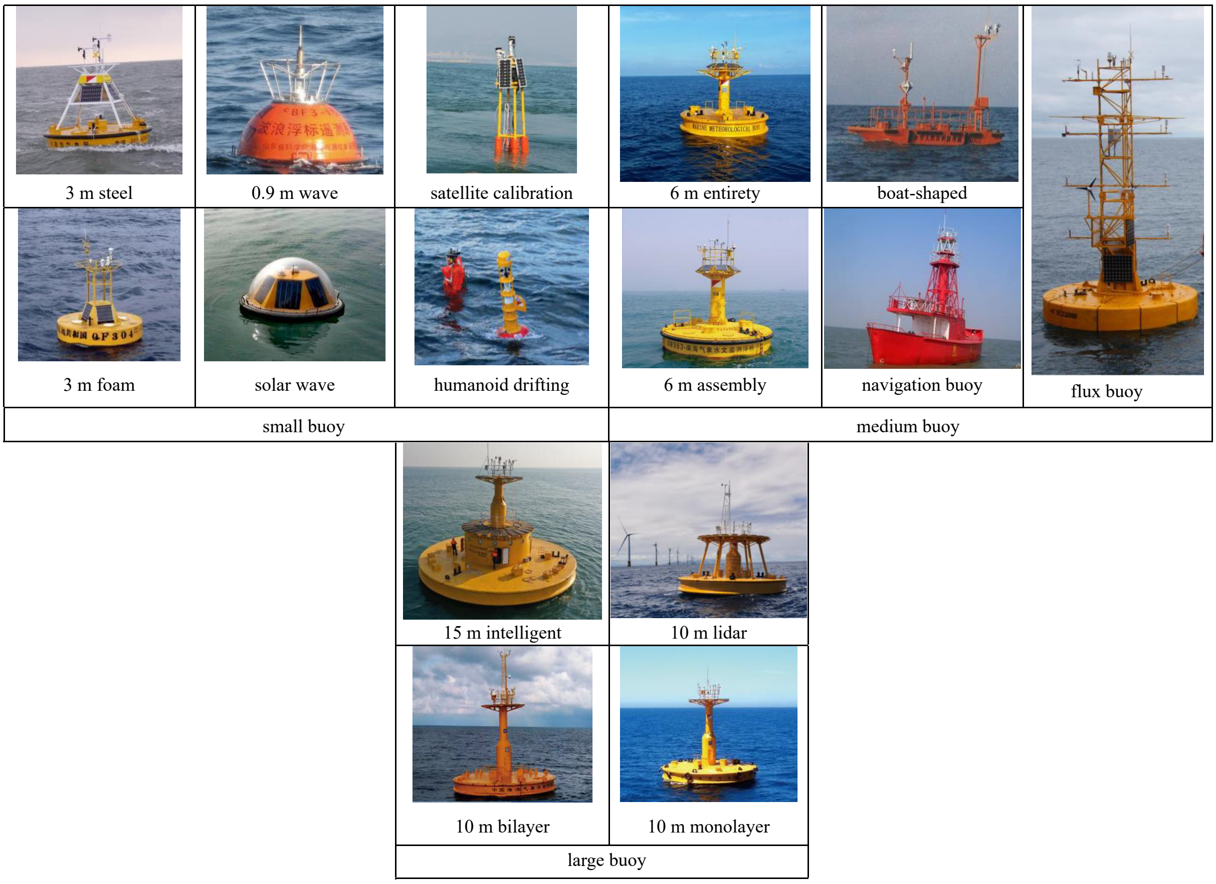

Fig. 2. Serialized ocean data buoys.

ic observation has gradually replaced manual observation and become the mainstream, the VOS measuring and reporting system realised the satellite real-time communication of observation data. China's first set of comprehensive VOS measuring and reporting system was manufactured in 1999. Later, in 2001, the set was employed for operational use by the State Oceanic Administration and was modified and upgraded first in 2006 and then in 2011, the VOS measuring and reporting system products formed were represented by CZY series of National Ocean Technology Center and XZC series of Institute of Oceanographic Instrumentation, Shandong Academy of Sciences (Dong and Zhang, 2016). In 2014, a modernised voluntary ship monitoring and forecasting instrument with a two-way communication function was developed and put into large-scale operational monitoring. Over generations of development, achievements have been made in techniques for shipboard-measuring of wind parameters, two-way communication and transmitting data, and multi-network fusion data transmission. Based on the aforementioned technologies, the VOS measuring and reporting system could meet the monitoring requirements of most types of ships, such as ocean surveillance ships, coast guard ships, cargo ships, passenger ships, fishing boats, etc.

2.3.3 *Development and current operational status of VOS measuring and reporting systems*

Presently, about 100 sets of VOS measuring and reporting systems are installed on China's voluntary ships (Peng, 2022), and these monitoring instruments have further succeeded in entering the international market. Dozens of units and organisations employ VOS measuring and reporting systems on their ships, which cover ocean surveillance ships, coast guard ships, cargo ships, passenger ships, fishing boats, special application ships, etc. Figure 3 shows VOS observation equipment and some VOS types.

VOS measuring and reporting system, a type of specialised marine monitoring equipment capable of operational monitoring, contributes greatly to the comprehensive development of China's marine monitoring network. Being a source of periodic monitoring data of marine meteorology and hydrology, this system compensates for the deficiency of the monitoring area of C-MAN station network and data buoy network, thereby enhancing the function of stereoscopic observation and monitoring network.

3 Development of operational *in-situ* marine monitoring and achievements in the key generic technologies

Through several generations of development and upgradation, the aforementioned three technological systems of operational *in-situ* marine monitoring have improved comprehensively, and presently, they are generally up to the latest standards for operational monitoring. Achievements in their key generic technologies are summarised in the following four representative aspects.

3.1 *Research on the measurement accuracy of motion conditions*

Ocean data buoy and VOS measuring and reporting system work on motion conditions that are prone to swaying and rocking, which make their operation more difficult than land observation that is performed under steady conditions. The accuracy of measurements such as wind speed, wind direction, wave height, wave direction, and precipitation depends heavily on the motion

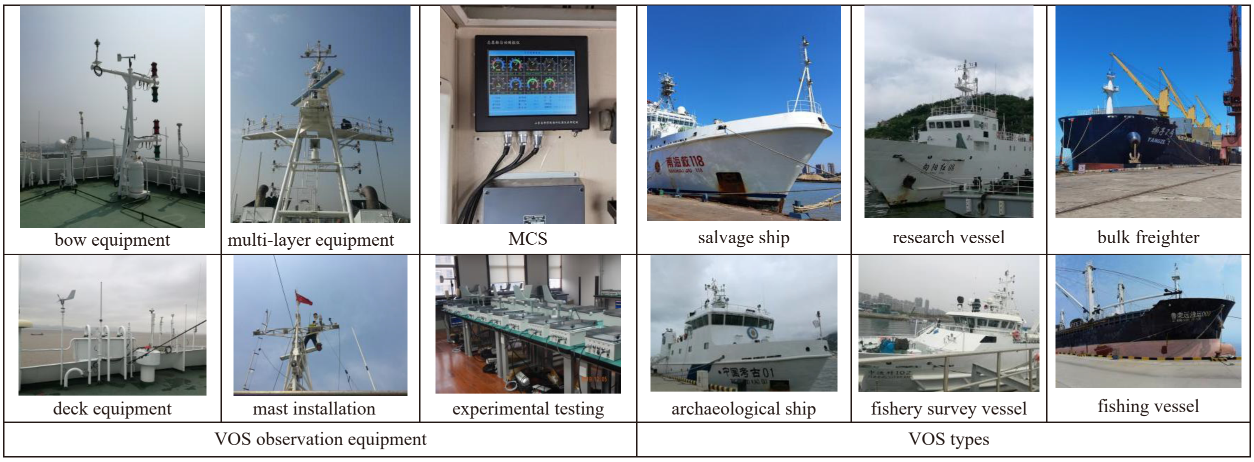

Fig. 3. Voluntary observing ship (VOS) observation equipment and some VOS types.

condition, and the measurement result is prone to deviations because of the effects of the motion of the floating carrier platform.

Relevant studies have led to advances in the following three aspects: ① the sensor measurement results are corrected by measuring the attitude information of the moving platform to obtain the true value of the environmental parameters; ② according to the dynamic characteristics of the sensor's motion attitude information, develop the dynamic compensation technology for the influence of the platform's motion attitude on the sensor; ③ develop sensors with dynamic compensation and self-correction functions.

3.2 *Developments in the operational in-situ marine ecological monitoring techniques*

In recent decades, the techniques of operational *in-situ* marine ecological monitoring have progressed, which has broken through the key technology of monitoring of marine biochemical parameters, leading to the development of a series of proprietary techniques and instruments (Cao et al., 2015; Shi et al., 2017; Wu et al., 2020). More than 10 types of *in-situ* instruments have been developed and applied extensively for monitoring total organic carbon (TOC) (Bi et al., 2020; Liu et al., 2007, 2010), chemical oxygen demand (COD) (Cao et al., 2017), chlorophyll (Guo et al., 2017; Wang et al., 2007), turbidity (Wang et al., 2007), dissolved oxygen (Zhang et al., 2014), oils, nutrients (Ma et al., 2016; Qi et al., 2019), total phosphorus and total nitrogen (Wu et al., 2019), pH in high precision, radionuclides (Liu et al., 2016), and other parameters.

Technical breakthroughs have occurred in the following aspects.

(1) *In-situ* monitoring of TOC and COD

The method of ozone oxidation-chemiluminescence qualitative and quantitative analysis of organic pollutants in seawater was developed, which realized *in-situ* and rapid monitoring of TOC and COD in seawater. This method is characterised by speedy, sensitive, and environment-friendly, it solved the problem of real-time capability and measurement accuracy. Compared with the conventional method of *in-situ* analysis, this method can accelerate the pace of analysis by 10 times (from 50 min to 5 min) and improve the measurement precision with a low least count of instrument by two orders of magnitude (from mg/L to μg/L).

(2) Instruments and sensors for seawater wet chemical analysis

A novel parallel flow injection analysis system was established for monitoring wet chemistry of seawater on the basis of microfluidic chip. This instrument can realise the *in-situ* analysis, based on marine wet chemistry, of nitrate, nitrite, phosphate, silicate, ammonium salt, total phosphorus, and total nitrogen, reduce the size of the pH instrument with a precision of 1‰, and is applicable in sensors. It also achieves long-term, automatic, and continuous monitoring of various key ecological parameters. Consequently, the system has been reformed for both on-site sampling and laboratory analysis.

(3) Optical sensor for *in-situ* monitoring of seawater quality

Developments have been made in key challenging areas of bright field determination, processing of weak fluorescence signals, and long-term reliable operations. Sensors with intellectual property rights have been developed for determining optical seawater chlorophyll, petroleum (polycyclic aromatic hydrocarbons), dissolved oxygen, and turbidity to realise quick and accurate *in-situ* monitoring of water quality by using optical sensors.

3.3 *Solution to the reliability and stability of observation instruments in harsh environment*

Because the C-MAN stations, ocean data buoys and VOS measuring and reporting systems, operate under high humidity, and salinity in rough seas, they face great challenges in terms of the reliability and stability of the instruments. In the process of industrialization and operational application of marine instruments and equipment, simulation test, real sea state test and fault diagnosis are important basis for objective evaluation of reliability and environmental adaptability of marine instruments and equipment, and the ultimate way to test whether equipment and technology achieve the expected results, it is also an essential link for marine high technology from laboratory to practical application (Guo et al., 2010, 2011; Jiang et al., 2020; Qi et al., 2012). Over years of development, the problem related to the operation of instruments under harsh environments has been gradually solved.

(1) Technical designs to resist harsh marine environments and ensure high reliability

Technical achievements have enabled the development of instruments that can resist harsh marine environments and maintain a high degree of reliability; these developments can solve other associated problems for ensuring long-term stability and reliability of marine monitoring. To resolve the problems of long-term, stable, and reliable marine monitoring, methods such as redundancy design, interactive monitoring, self-diagnosis technique, and self-adaptation control are adopted, and innovative methods for the parallel operation of dual machines have been developed. The reliability of the measured data has enhanced, and a control system for data acquisition has been developed. The control system can adapt to harsh marine environments and possess high reliability, universality, and configuration flexibility. Self-diagnosis technologies, including the fault condition alarm and real-time monitoring of operations under harsh environments, have been developed for monitoring buoy sensors, data transmission, and power supply.

(2) Techniques of platform-based sensors for *in-situ* water quality monitoring

Based on the study "Technological System of Continuous Marine Ecological Environment Monitoring in Key Monitoring Areas", which was conducted under National High-tech R&D Program (863 Program) and by applying automatic techniques of water intake, sampling, measurement, and cleaning, further studies have been conducted to develop techniques for long-term and continuous platform-based operation of sensors for *in-situ* water quality monitoring. These studies have led to the development of prototypes for procedures such as automatic water intake, measurement, drainage, and cleaning for monitoring parameters such as marine temperature and salinity, pH, and dissolved oxygen. Results from a long-term application of this system in large buoys indicate that this technique can eliminate biological turbidity and provide stable and reliable measuring data. Tests of the sensors that had been in use during a 6-month continuous operation indicate only a small amount of dirt on the surface of the sensor and reveal no biological attachment, indicating that the aforementioned system can effectively extend the service life of water quality sensors.

(3) Improvement of materials and techniques

To improve the system reliability, the instruments that collect and analyse the platform data, measuring systems, and communication system are all designed in modules and with low power consumption. The electrical plug and socket connectors adopt the inner bayonet locking structure and are of excellent quality comparable to high quality products, while being light in weight and small in size. In addition, the bayonet connection allows the quick plugging and unplugging. Overall, the system presents good sealing performance, high tensile strength, and strong corrosion resistance. The electrical connectors are treated with special watertight glue filling and three proofings (anti-mold, anti-moisture, anti-salt spray), and the instruments are equipped with in-built desiccants to keep the inside air dry, which ensure the service life of electronic components for marine operations.

3.4 *Solutions to the operation of monitoring instruments under extreme marine environments*

Under extreme marine environmental conditions, for example, when a typhoon passes over, the survival and normal operation of monitoring instruments such as buoys must be safeguarded for operational monitoring because this extremity only makes the observed data even more precious and important. To ensure that the buoy does not overturn and there is no failure of cable or chain and anchor dragging, the stability design of buoy, optimisation of mooring, and application of innovation in materials and techniques must be considered. Starting with aspects concerning the operation of buoy under extreme marine environment of a typhoon that include hydrodynamic modelling and computational simulation, tank pool reduced-scale modelling, mooring and anchoring optimisation, and application of innovative materials and techniques, achievements have been made in techniques to ensure reliable mooring in extremely harsh marine environments and thus to ensure a reliable and stable buoy operation.

4 Future development and innovation of the operational *in-situ* marine monitoring technology

4.1 *Development and innovation prospects of the C-MAN station technology*

Compared with other monitoring systems, the C-MAN station technology boasts a longer history, and thus, it is more mature in technique development. Furthermore, it operates in an environment-friendly manner for long term and ensures stable and accurate collection of marine hydrometeorological data, compared with the data buoys and VOS measuring and reporting systems. In recent years, with the development in the field of science and technology, techniques in C-MAN station observation has also progressed greatly, with decreased size, high performance, and reduced price. From the technical perspective, the C-MAN station will be focused on improving the adaptability, multifunction property, reliability, and reusability of instrument to make them applicable to various environments, occasions, and requirements in future development.

4.2 *Development and innovation prospects of the ocean data buoy technology*

Presently, ocean data buoys have seen the development of products in series and up to a considerable scale, and thus, they generally meet the requirements of offshore marine monitoring. However, due to the development of global marine three-dimensional monitoring networks and the implementation of "Smart Ocean" and "ecological ocean" strategies, a new generation of integrated intelligent buoys is required. Intelligent buoy is the "ganglion" of "Smart Ocean" information system. It will become the most important node and the most convenient relay for interconnection with C-MAN stations, unmanned autonomous mobile platforms, voluntary observing ships, remote sensing satellites and undersea observatory network. The development level of intelligent buoy technology is related to the establishment of China's global marine three-dimensional monitoring system and the construction of "Smart Ocean" engineering.

Considering the shortage of existing buoys, the integrated intelligent buoy is expected to be the next step for developing the buoy system. However, only tentative and scattered studies on this concept have been conducted, and no significant research outcome has been achieved. The integrated intelligent buoy stands out as being technologically innovative and forward-looking, it is considered smart based on the following aspects:

(1) Technology for the integrated marine information measurement by smart sensor

The development of various smart sensors, such as acoustic, optical, electromagnetic, chemical, or biological sensors, is essential for compatibility with buoys. Such sensors can retrieve information in the form of figures, graphics, acoustics, or videos of environment, targeting underwater to air-sea interface environments in a long-term, continuous, real-time, and three-dimensional manner. Thus, a large amount of data will be stored and transmitted.

(2) Technology for intelligent perception of knowledge products in the field of marine information

For the buoys that are sensitive to data quality, intelligent control should be delivered so that *in-situ* self-calibration and normalisation can be performed on data. New methods such as artificial intelligence, machine learning, and big data mining can be incorporated to advance the treatment of collected data. In addition, it is necessary to develop high-grade data forecast and marine information products that are scientific, efficient, and sensitive to safety management and can sense the state of a buoy and its surroundings.

(3) Technology for automatic and intelligent applications of buoys

Each buoy will be communicated to surrounding buoys to share information that can enable independent intensive cooperative monitoring according to the observation requirements. In addition, the buoy will be capable of ① network monitoring with other instruments in a rapid and flexible manner; ② communication and energy relaying for both surface and underwater operations; and ③ automatic position changing. The application system of marine buoys will be developed to be requirement- and target-specific. A network of marine intelligent buoys will be formed to meet specific requirements for preventing marine ecological disaster, surveying fishery resources, and ensuring marine and underwater navigation safety.

(4) Technology for active response of buoys

Intelligent buoys will be able to carry failure diagnosis and intelligent control on instruments based on the data acquired in smart sensing. In addition, the sensor will ① conduct independent calibration and maintenance; ② realise smart allocation, management, and supply of energy; and ③ measure and control its motion attitude in high precision. In summary, various methods will be integrated to avoid damage to the buoy.

4.3 *Development and innovation prospects of the VOS measuring and reporting system technology*

Building on current development, the future innovation of the VOS measuring and reporting system is concerned with two main aspects: ① expanding the coverage of monitoring environmental parameters, for example, enabling the monitoring of wave, current, tide, water quality, and other parameters; ② conducting research and applying stereo-meteorological observation technologies, which mainly refer to atmospheric waveguide and regional weather forecasts. Innovation and application of technologies in the aforementioned fields will primarily be the solution to problems of in-ship motion interference to the measurement accuracy.

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