Research on the Application Status and Prospect of Small Satellite in Meteorological Monitoring

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Abstract: Small satellites have become an important supplementary part of meteorological monitoring due to their low cost, high flexibility, and networking advantages. They can monitor multiple atmospheric parameters, wind fields, clouds, and precipitation, enhancing traditional observation methods and collaborating with large satellites to improve spatial and temporal data resolution. Its application has expanded from technical exploration to practice, supporting weather forecasting and disaster warning. In the future, as sensor accuracy improves and intelligent networking integrates with AI, its applications will expand into urban fine services and polar monitoring, promoting the creation of a complete industrial ecosystem. Small satellites are reshaping the pattern of meteorological monitoring and providing key support for building an efficient global meteorological service system.

1. Introduction

1.1 Research Background

Meteorological monitoring is a crucial foundation for human beings to cope with climate change and prevent and reduce disasters. Its core lies in supporting weather forecasts, disaster early warning, and climate research by continuously obtaining multi-dimensional data about the atmosphere, ocean, and land. Traditional meteorological monitoring depends on ground observation stations, sounding balloons, and large meteorological satellites. However, the distribution of ground stations is uneven, making it challenging to cover remote areas such as oceans and polar regions. Although the observation range of large satellites is wide, several challenges arise, including a long research and development cycle, high costs, and slow update iterations, which hinder the ability to meet the needs of fine and high-frequency monitoring.

In recent years, small satellite technology has risen rapidly, with weights typically ranging from below 500 kilograms to as small as several kilograms. The advantages of small satellites include a short research and development cycle, low cost, and flexible launch. Due to the progress of sensor miniaturization, communication technology, and constellation networking technology, small satellites have been able to effectively detect atmospheric temperature and humidity, wind field, cloud system, and precipitation. At present, many countries and commercial organizations around the world have deployed small satellite meteorological observation constellations, which have gradually become an important supplement to the traditional meteorological monitoring system. In this context, this study explores the application and future potential of small satellites in meteorological monitoring, which is crucial for improving the meteorological observation network and enhancing monitoring capabilities [1].

1.2 Research Purpose

The purpose of this study is to systematically summarize the application status of small satellites in the field of meteorological monitoring, analyze their technical characteristics and application scenarios, and look forward to the future development trend. The specific objectives include:

First, it defines the key application direction of small satellites in meteorological monitoring. By combining the existing research and practice, this paper summarizes the technical principles and

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application effects of small satellites in atmospheric parameter detection, wind field monitoring, cloud and precipitation observation, and clarifies the functional differences and complementary relations between them and large meteorological satellites.

Second, it analyzes the limitations of current meteorological monitoring by small satellites. It identifies existing problems from the technical level, application level, and industrial level, and provides targeted reference for subsequent development.

Third, this study looks forward to the potential of small satellites in meteorological monitoring. This text explores the application prospects of sensor technology, artificial intelligence, and constellation networking. It focuses on their potential uses in fine meteorological services, compensating for blind spots in global observation networks, and responding to disaster emergencies. Additionally, it provides guidance on related technological research and development, policy formulation, and industrial planning.

The research provides a clear theoretical framework and practical reference for practitioners, researchers, and policy makers in the meteorological field. It promotes the use of small satellites to better serve the meteorological monitoring cause.

1.3 Research Significance

The significance of this study is embodied in theory, practice, and society:

Theoretically, this research is beneficial in enriching the research content of the meteorological monitoring technology system. Traditional meteorological monitoring research mostly focuses on large satellites and ground equipment, and there is little systematic analysis of small satellites. By summarizing its technical principles, application scenarios, and development rules, the theoretical framework of meteorological observation technology will be improved, and new ideas will be provided for interdisciplinary research.

In practice, the research findings can provide guidance for the technical optimization and application expansion of small satellite meteorological monitoring. After evaluating the advantages and disadvantages of the current application, researchers can suggest directions for technical improvements. They will serve as a reference for project planning by commercial institutions and scientific research units, ultimately promoting the enhancement of small satellites from basic observability to high-precision and high-reliability observation capabilities.

For societal development, it enhances support for meteorological monitoring, which is crucial for public safety and social development. The low cost and high flexibility of small satellites can make up for the traditional monitoring network, improve its early warning ability for typhoons, rainstorms, and droughts, and reduce disaster losses. Moreover, its high-frequency and refined data can provide customized services for agricultural production, urban management, aerospace, and other fields, and assist the social economy to operate efficiently. It will promote the development of small satellite meteorological monitoring, and also promote the advancement of aerospace manufacturing, data services, and related industries, yielding significant economic and social benefits.

2. Overview of Small Satellites

2.1 Definition and Classification of Small Satellites

Small satellites are a spacecraft compared with traditional large satellites. They are usually defined by weight, which generally refers to satellites weighing less than 500 kg. This definition is not absolute but represents an industry consensus that has gradually developed with technological advancements. Its purpose is to differentiate it from larger satellites based on tonnage.

There are two common classification methods. According to weight, satellites can be categorized into micro-satellites, nanosatellites, picosatellites, etc. The weight of micro-satellites ranges from 100 to 500 kilograms, while nanosatellites typically weigh between 1 and 10 kilograms. Picosatellites are the lightest, often weighing less than 1 kg. According to the function, it can be divided into observation type, communication type, and technical test type. Among them, the observation type is the most widely used in meteorological monitoring, and it is mainly equipped with various sensors to complete data acquisition tasks. This classification not only reflects the scale difference of small satellites, but also reflects their functional diversity [2].

2.2 Characteristics of Small Satellites

The characteristics of small satellites are closely related to their original design intention, and the core is to break through the limitations of traditional large satellites.

One of its characteristics is lightweight and small size. Compared with large satellites, small satellites are more compact in structure, which helps to reduce material consumption and launch load and reduce the total cost. The second feature is the short research and development cycle. Due to the high degree of technical integration and relatively simple system, the cycle from design to launch is usually several months to two years, which is much faster than the cycle of several years for large satellites [3]. The third feature is flexible launch. It can be launched into orbit using various methods, including carrying large satellites, special small rockets, and other approaches, without relying on exclusive launch resources, which further lowers the threshold. The fourth feature is strong networking ability. The function of a single satellite is limited, but multiple satellites can form constellations and work together. Due to its large number, it compensates for the shortcomings of single satellite performance, thereby improving coverage and frequency of observation. These characteristics make small satellites more advantageous in rapid response and large-scale applications.

2.3 Development Course and Present Situation of Small Satellites

The development of small satellites began as a complementary effort to large satellites. Due to technological limitations in the early days, small satellites had simple functions and were primarily used for technical verification, which hindered their widespread adoption. With the progress of microelectronics, new materials, and communication technology, especially the miniaturization of chips and the improvement of sensor performance, small satellites are gradually gaining practical value [4].

In recent years, small satellites have entered a stage of rapid development. The number of global launches has greatly increased, and the application fields have expanded from the initial technical experiments to many fields, including meteorological monitoring, environmental observation, and communication. Commercialization is a key driving force, enabling many enterprises to reduce costs through standardized design and mass production. In addition, scientific research institutions in various countries are also actively deploying small satellite constellations to improve observation efficiency. At present, small satellites have gradually become an important part of the aerospace field from a complementary role, and their application potential in meteorological monitoring is being continuously tapped.

3. Application Status of Small Satellites in Meteorological Monitoring

3.1 Atmospheric Parameter Detection

Atmospheric parameter detection is the basic application of small satellites in meteorological monitoring, mainly focusing on obtaining data related to the composition in the vertical structure of the atmosphere. Small satellites can be equipped with a microwave radiometer and a GNSS occultation receiver. By receiving electromagnetic radiation at different levels of the atmosphere or refraction information of navigation satellite signals, key parameters such as temperature, humidity, and air pressure can be retrieved.

Compared with ground observation, it has the advantage of wide coverage and can fill the observation gaps in remote areas such as oceans, deserts, and polar regions. The networking of several small satellites can realize the high-frequency updating of the global atmospheric temperature and humidity profile, provide initial field data for the numerical weather forecast model, and improve the forecast accuracy. At present, the application is mature, and the data are widely used to analyze the characteristics of atmospheric circulation and monitor the change of tropopause height, which has become an important supplement to traditional sounding methods.

3.2 Wind Field Monitoring

Wind field monitoring is a crucial component of small satellites in meteorological monitoring, particularly for observing ocean and upper air wind fields. Small satellites can receive microwave signals reflected by the sea surface through a scatterometer, and calculate the wind speed and direction of the sea surface according to the Doppler frequency shift. Moreover, it can also retrieve information on the upper air wind field by tracking the movement of cloud tops or aerosols. It is characterized by high observation frequency and can capture the wind field evolution of fast-changing weather systems such as typhoons and tropical cyclones.

Due to the limited coverage of a single satellite, experts usually form a global wind field observation network through multi-satellite networking to make up for the lack of time resolution of large satellites. At present, the data has been used to improve the marine weather forecast, enhance the early warning ability of storm surge and strong wind disasters, and play a role in ocean shipping and fisheries.

3.3 Cloud and Precipitation Monitoring

Cloud and precipitation monitoring depends on optical imagers and microwave radars carried by small satellites. Optical equipment can capture the shape, coverage, and moving trajectory of clouds, identify different cloud types such as cumulus clouds and stratus clouds, and provide a basis for judging the development of weather systems. Microwave radar penetrates the clouds to detect the liquid water content, precipitation intensity, and vertical structure, making it especially suitable for monitoring strong convective weather, such as rainstorms and thunderstorms.

The advantage of small satellites lies in their ability to capture small and medium-scale cloud systems and precipitation systems, which can supplement the observation blind spots of ground radar in mountainous areas, oceans, and other regions. At present, its data has been used for short-term weather forecasts, which helps to identify heavy precipitation areas and enhance the early warning timeliness for disasters such as urban waterlogging and mountain torrents.

3.4 Monitoring of Other Meteorological Elements

In addition to the core meteorological elements, small satellites also play a role in monitoring several meteorological elements. In terms of atmospheric composition, small satellites equipped with hyperspectral sensors can monitor ozone concentration and aerosol optical thickness, providing data for studying ozone layer destruction and air pollution diffusion. In monitoring the earth's surface and snow conditions, the surface temperature is retrieved by an infrared sensor. At the same time, a microwave radiometer detects the thickness of sea ice and the extent of snow coverage. This technology supports polar climate research and helps predict snowmelt runoff.

Some small satellites can be used to observe changes in vegetation cover and land evapotranspiration, which indirectly reflect the dry and wet conditions of the regional climate. These applications are highly relevant, bridging gaps in traditional observation and enhancing the scope of meteorological monitoring.

3.5 Cooperative Observation of Small Satellites and Large Meteorological Satellites

The collaboration between small satellites and large meteorological satellites constitutes a pivotal component of the contemporary meteorological observation system. The primary benefits of large-scale meteorological satellites are twofold. Firstly, they are equipped with high-precision and high-stability instruments, which enable the collection of long-term and overall standard meteorological data. Secondly, they serve as the standard for climate research and operational forecasting, setting the benchmark against which other satellite data is measured. The utilization of small satellites is advantageous due to their capacity for adaptability, high operational frequency, and cost-effectiveness. These satellites are particularly well-suited for the observation of local and short-term weather phenomena.

For the cooperation of the two, large satellites provide a global background field, while small satellites offer detailed data in key areas or frequently updated information. It creates an observation network that combines global and local perspectives, as well as long-term and short-term data. For example, large satellites acquire the global sea surface temperature distribution. In contrast, small satellites encrypt and monitor the sea surface temperature changes around the typhoon path to jointly improve the forecast accuracy. This model effectively utilizes their advantages while minimizing the risks associated with a single satellite system, making it the standard approach for meteorological monitoring.

4. Application Prospect of Small Satellite in Meteorological Monitoring

4.1 Development Trend of Technology

The technical development of small satellites in meteorological monitoring will focus on improving accuracy, optimizing efficiency, and integrating functions. The advancement of sensor technology is poised to make significant strides, with optical and microwave sensors undergoing further miniaturization and enhancement in accuracy. For example, the chip-level microwave radiometer can realize higher resolution detection of atmospheric temperature and humidity, and the micro lidar can capture the vertical distribution of aerosol more accurately. Constellation networking technology is being upgraded for intelligent collaboration. With inter-satellite communication and an autonomous control algorithm, multiple satellites can dynamically adjust their observation areas, allowing for focused high-frequency monitoring of typhoons and rainstorms while reducing data redundancy [5].

In the data processing, researchers will deeply integrate artificial intelligence, and the edge computing chip will be deployed in the satellite load to realize the on-orbit preprocessing of some data and shorten the time difference from observation to application; On the ground side, the machine learning model is utilized to optimize the data inversion algorithm and enhance the recognition accuracy of clouds, precipitation, and other elements. The application of new material technology will reduce the weight of the satellite, prolong the on-orbit life, further lower long-term observation costs, and support the continuous and stable output of meteorological data.

4.2 Expansion of Application Areas

The application scenarios of small satellite meteorological monitoring will become refined, providing comprehensive coverage and significant emergency response capabilities. In the domain of urban meteorology, the networking of high-density constellations facilitates minute-level monitoring of the urban heat island effect, local small-scale circulation, and pollutant diffusion. This capability provides accurate data for urban ventilation corridor planning and air pollution emergency control. In remote and weather-extreme areas, traditional observation blind areas such as polar regions, plateaus, and oceans will be made up, for example, the melting rate of the Antarctic ice sheet and the change of Arctic sea ice will be continuously monitored through polar orbiting small satellite clusters, providing key data for global climate change research [6].

In the field of disaster emergencies, the rapid response capability of small satellites will become more prominent. After the disaster, relevant personnel can quickly launch or adjust the orbit of the on-orbit satellite to obtain meteorological data in the disaster area within a few hours, assist in judging the landslide risk and typhoon path deviation caused by heavy rain, and provide real-time support for rescue decision-making. Furthermore, it will be profoundly interwoven with agriculture and aviation. To illustrate, it will provide regional precipitation and temperature forecasts for agricultural areas, as well as turbulence warnings for flight route planning. Consequently, meteorological data will directly contribute to industrial modernization.

4.3 The Development Prospect of the Industry

Small satellite meteorological monitoring will promote the formation of a full chain, multi-agent, and global industry. Satellite manufacturing will become standardized and mass-produced. Modular design reduces R&D costs, lowers the cost per satellite, and encourages more small and medium-sized enterprises to get involved. The launch service will exhibit enhanced flexibility, and the standard launch of small launch vehicles will achieve on-demand launch, thereby reducing the satellite orbit cycle. The data service market will expand rapidly. In addition to the traditional meteorological departments, agricultural enterprises, insurance companies, and new energy enterprises will become core users. For example, insurance companies can design crop insurance products based on regional precipitation data from small satellites, while new energy enterprises utilize wind field data to optimize wind power locations [7].

International cooperation is expected to become an important trend. Countries can enhance their global defense capabilities against meteorological disasters by sharing small satellite observation data and jointly building transnational constellations. For example, for the E1 Nino phenomenon, the prediction accuracy of its occurrence time and intensity is improved through the cooperative observation of multinational satellites in the Pacific region. Relevant policies and regulations will be gradually improved to promote a balance between data sharing and commercial application, ensuring the industry's sustainable development.

5. Conclusion

The application of small satellites in meteorological monitoring has gone from technical exploration to practice, and has become a key force to improve the global meteorological observation system. The application's status, characterized by its cost-effectiveness, adaptability, and networking advantages, has demonstrated a unique value in atmospheric parameter detection, wind field monitoring, cloud and precipitation observation. This application not only addresses the limitations of traditional ground observation and large-scale satellite monitoring in remote areas and small and medium-scale weather systems, but also enhances the temporal and spatial resolution and application breadth of meteorological data through cooperation with large-scale satellites. This enhancement provides substantial support for numerical weather forecasting, disaster early warning, and climate research.

Looking ahead, the development of small satellites will increasingly showcase accelerated technical advancements, broadened application scenarios, and an enhanced industrial ecosystem. The improvement of sensor precision and the breakthrough of intelligent networking technology will promote it to leap from energy observation to high-precision and high-reliability observation. Moreover, its application in the fields of refined urban services, polar monitoring, and disaster emergency will further release its supporting potential for social and economic development. The advancement of standardized manufacturing, commercial operations, and international cooperation will enhance the formation of a complete industrial ecosystem and reduce the barriers to meteorological monitoring.

Small satellites are reshaping the mode and pattern of meteorological monitoring. In the future, researchers need to constantly promote technological innovation, strengthen cross-disciplinary collaboration, and improve data-sharing mechanisms and policies to better address climate change and disaster prevention and mitigation. They will contribute to the development of a more accurate and efficient global meteorological service system.

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