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Observation of Ocean Winds Using Satellite-based GNSS+R Technology

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Abstract. In recent years, due to climate change, there has been a significant increase in sea surface winds, leading to multiple iterations of satellite-based GNSS+R (Global Navigation Satellite System Reflectometry). The offshore wind measurement technology utilizing GNSS+R offers continuous and widespread capabilities. GNSS+R reflected signals have been extensively researched internationally for typhoon detection and disaster prediction applications. Despite its emerging nature, there is a lack of comprehensive articles detailing the development history of GNSS+R. Therefore, this paper aims to thoroughly review GNSS+R's evolution by examining the connection between signals from surface mirror reflection and sea surface wind. Starting with the principles of ocean surface wind measurement proposed by NASA in 1997, the introduction of the Z-V model, and the advancement of GNSS+R remote sensing techniques, such as BP neural network-based GNSS+R sea surface wind speed retrieval methods, this paper traces the significant advancements in inversion technologies. It also discusses the international development of GNSS+R for offshore wind measurement, from the initial concept to the widespread applications of projects such as the UK's Surrey company, the European Space Agency's GEROS program, and NASA's CYGNSS. Additionally, the paper covers the domestic launches of the Wind Catcher-1A and 1B satellites and the application of BeiDou navigation satellites. It summarizes the future technological advancements in GNSS+R remote sensing both domestically and internationally, exploring its potential for acquiring sea surface wind field information and predicting flood disasters. Finally, it emphasizes the challenges of signal interference and inversion algorithm accuracy with the hope of overcoming these technical hurdles.

Keywords: GNSS+R; Sea Surface; Wind Speed; Remote-Sensing.

1. Introduction

The global climate has become increasingly variable in recent years, underscoring the urgent need for effective and reliable ocean monitoring. As climate change continues to impact weather patterns and marine ecosystems, measuring wind speed at the sea surface has become a crucial component of environmental monitoring efforts. Sea surface wind plays a significant role in the energy exchange between the ocean and the atmosphere, influencing climate dynamics and a number of useful applications, such as navigation, fishing and weather forecasting. Traditional methods for measuring sea wind primarily include buoys and meteorological stations. Buoys are capable of performing automatic and continuous long-term measurements of wind speed, providing valuable data over extended periods. However, their effectiveness is often limited by a relatively small coverage area, which can restrict the amount of data collected. Additionally, the maintenance costs associated with buoys can be quite high, especially in remote or harsh marine environments. Conversely, meteorological stations utilize advanced ultrasonic technology to conduct direct measurements of sea wind. While this method is known for its high precision, it also faces significant challenges. These include limited spatial coverage, prohibitive construction costs, and the potential for environmental factors—such as precipitation or nearby obstructions—to impact the accuracy of the readings. Amid these challenges, a promising advancement with regard to measuring ocean winds is GNSS+R (Global Navigation Satellite System Reflectometry), an Innovation in technology that began to gain traction in the early 21st century.

GNSS+R leverages existing GNSS systems in conjunction with remote sensing technology to transmit L-band electromagnetic waves. By analyzing the time delay between direct signals and those reflected off the sea surface, as received by both satellites and surface-based receivers, researchers can infer critical information about sea surface roughness and various related characteristics. The inherent all-weather and real-time capabilities of satellite L-band signals make GNSS+R exceptionally well-suited for a wide range of applications, including space meteorology, typhoon monitoring, disaster prediction, and particularly in measuring sea surface wind speed. Despite its promising potential, GNSS+R remains a relatively young technology, and there has been a noticeable lack of comprehensive review articles that summarize its development and potential applications. This gap highlights the necessity for a detailed overview of GNSS+R's evolution and current state.

Therefore, this paper aims to trace the development of GNSS+R from the late 20th century to the present, integrating the latest research advancements and findings. This study could provide scientific insights that could inform future developments in this promising area of study, ultimately contributing to more accurate and widespread methods for monitoring oceanic wind conditions. Through this comprehensive exploration, this study not only highlights the capabilities of GNSS+R but also fosters greater interest and investment in this innovative technology, paving the way for enhanced environmental monitoring and better-informed decision-making in various sectors.

2. Measurement Principle of Sea Surface Wind Speed

2.1. Basic Principles and Process

The GNSS+R system is a crucial measurement device in remote sensing disciplines. GNSS+R measurement technology falls under the category of dual-base radar. It technically utilizes the time delay between direct signals from GNSS satellites that eventually arrive at the sea's surface and the signals reflected from it. By analyzing the geometric relationships between the GNSS satellites, the receiver, and the mirror reflection point, as well as the differences between the direct and reflected signals, it is possible to retrieve information regarding the characteristics and roughness of the sea surface, as illustrated in Figure 1 [1].

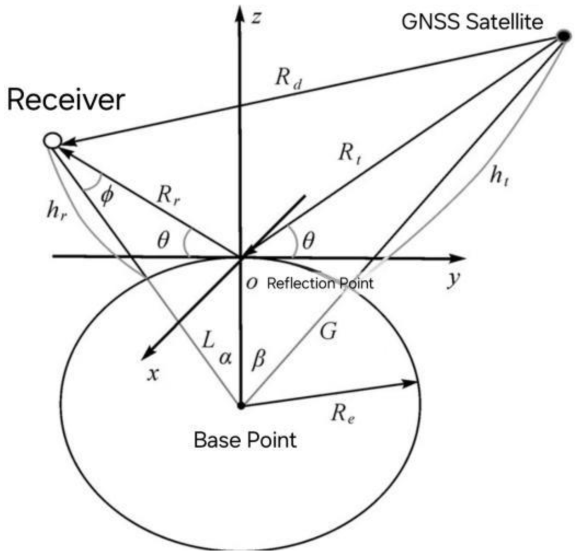

Figure 1. Geometric relation of GNSS specular reflectometry [1]

2.2. Principle and Progress of Inversion Technology in GNSS+R Systems

In GNSS+R systems, inversion technology is a critical method for measuring sea surface wind speed, with its accuracy directly reflecting the precision of wind speed measurements.

In 1997, NASA's Langley Research Center and Colorado State University initiated research on inversion algorithms for sea surface wind measurement using GNSS+R. Based on experimental findings, wind causes the sea surface to get rougher. According to the principles of sea surface wind field inversion, the roughness of the sea surface is positively correlated with the peak power of the signal that is reflected off the sea surface. This implies that as wind speed increases, the energy of the reflected signal tends to flatten, while it becomes steeper as the speed decreases, as shown in Figure 2 [2][2]. Consequently, based on the GNSS+R reflected echo signal's energy, the wind speed over the sea surface can be reversed.

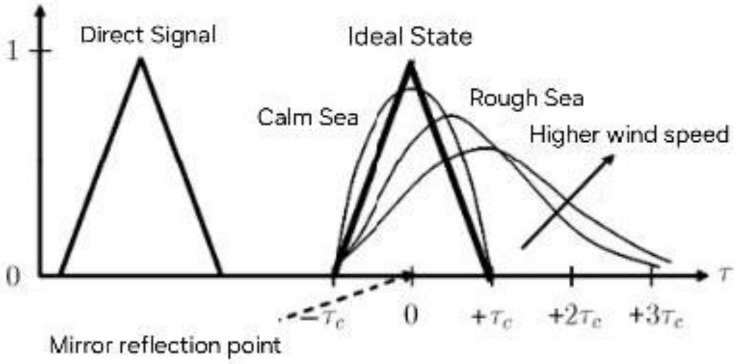

Figure 2. The relationship between wind speed and reflected signal power [2][2]

In 1999, the ZV model was put forth by Zavorotny and Voronovich [3], which was one of the earlier, more mature inversion models. By comparing the trailing edge of the ZV model with measured data, the actual wind speed could be determined. However, this model did not account for Bragg scattering caused by slight slopes on the sea surface outside the glint region. In 2002, Elfouhaily et al. made corrections to the ZV model to address these limitations [4]. In 2014, Clarizia et al. utilized GNSS+R remote sensing observations to obtain five Delay-Doppler Maps (DDMs) and established a minimum variance model for estimating wind speed based on regression analysis from the empirical Geophysical Model Function (GMF). Experimental results showed that the root mean square error (RMSE) of the observed wind speed using minimum variance was significantly lower than when using a single observation. In 2019, Gao et al. introduced a method for inverting sea surface wind speed using GNSS and radar data, which relies on a backpropagation (BP) neural network approach [5]. This innovative technique enhances the accuracy of wind speed estimations by leveraging advanced machine learning algorithms. The RMSE for wind speeds below 20 m/s and above 20 m/s were 1.21 m/s and 2.54 m/s, respectively, which was more accurate than the Delay-Doppler Map Average (DDMA) method. In 2020, Liu et al. corrected the geometric factors in bistatic radar wind speed inversion, achieving an RMSE of 2.61 m/s. The corrected bistatic radar cross-section effectively inverted sea surface wind speeds [6]. In 2021, Du et al. developed a Cumulative Distribution Function (CDF) matching method for the measurement of wind speed by GNSS+R [7]. This method matches the inversion and reference wind speed sequences using the CDF, and corrects wind speed deviation sequences using the least squares method, effectively reducing the error between DDM features and wind speed. Experimental results showed that the RMSE decreased by 6% for wind speeds below 5 m/s and by 15% for wind speeds between 12 and 20 m/s.In 2024, Zhang et al. applied the Random Forest algorithm to estimate wind speed using coastal GNSS-R data obtained from the Dongqing No. 5 oil platform. The analysis revealed RMSE of 1.02 m/s for the training set R1, while the RMSE for the training set R^2 was 1.55 m/s [8]. These findings suggest that the Random Forest algorithm exhibits strong performance in wind speed estimation and is a promising method for GNSS+R sea surface wind speed retrieval.

3. Applications of GNSS+R in Ocean Wind Observation

3.1. International Applications

The GNSS+R technology was first proposed around the 1990s. Over the past few decades, sea surface GNSS+R technology has evolved into three distinct observation modes: ground-based, airborne, and satellite-based. Among these, satellite-based observation stands out as the most efficient, convenient, and promising for future development due to its ability to cover vast areas and provide high-resolution data in real-time. In 2003, Surrey Satellite Technology Limited initiated the UKDMC (United Kingdom Disaster Monitor Constellation) satellite launch program. This project marked a significant milestone as it was the first satellite to carry a GNSS+R payload. Through this initiative, the sensitivity of GNSS+R to weak surface reflection signals from both the sea and land was confirmed, paving the way for advanced applications in environmental monitoring and disaster response. In 2014, the European Space Agency launched the GEROS (GNSS Reflectometry Radio Occultation and Scatterometry) program, deploying the TechDemoSat-1 satellite [9]. This mission focused on a variety of applications of remote sensing across land and sea, further demonstrating the versatility of GNSS+R technology. The data gathered from TechDemoSat-1 provided invaluable insights into atmospheric conditions and surface characteristics, enhancing our understanding of environmental dynamics. In 2016, NASA successfully launched the CYGNSS (Cyclone Global Navigation Satellite System), a satellite system that contained eight satellites designed specifically for monitoring wind speeds during tropical cyclone events. This mission is considered a pioneering effort in GNSS+R development, focusing on detecting the most intense winds within these storms. By providing critical data on cyclone behavior, CYGNSS significantly enhances the accuracy of hurricane path and intensity forecasts, which is vital for disaster preparedness and response. By 2020, with the successful completion of the CYGNSS constellation and the launch of the UK-TDS1 satellite, international research on satellite-based GNSS+R entered a new and dynamic phase. This period witnessed substantial technological advancements and an expansion of applications across various fields, including disaster monitoring, maritime meteorology, and climate research. The increasing interest in GNSS+R has led to innovative solutions for addressing pressing environmental challenges, such as tracking storm systems and monitoring sea surface changes.

Additionally, the European FSSCat (Federated Satellite Systems Cat) program aims to deploy a 6U CubeSat equipped with GNSS+R technology specifically designed to enhance ice content detection in polar regions [10]. By leveraging satellite data, FSSCat seeks to improve our understanding of polar climate dynamics and contribute to global climate change research.

Overall, the development of GNSS+R technology reflects a significant advancement in remote sensing capabilities, offering the potential for improved environmental monitoring and enhanced disaster management strategies worldwide.

3.2. Domestic Applications

China's research on GNSS+R for sea surface wind retrieval began in 2002, with the Chinese Academy of Sciences initiating studies in the Qingdao and Yellow Sea regions. In 2006, Zhou et al. processed airborne data from NASA's Michael project, demonstrating the feasibility of using GPS-reflected signals for retrieving sea surface wind fields [11]. In 2019, China launched the Wind Catching Satellites A and B, which can measure wind speeds ranging from 2 to 70 m/s with a deviation in 2 m/s. This marked the first time that a satellite equipped with GNSS+R payloads was used to measure sea surface wind information, aiding in early flood disaster predictions and geological surveys. The following year, the Fengyun-3E satellite was integrated with GNSS+R technology and occultation detection payloads, significantly contributing to ocean altimetry and wind measurement [12]. In June 2020, the successful deployment of the BeiDou-3 (BDS-3) satellites marked a significant milestone in the completion of the BeiDou navigation satellite system, which enables the system to offer comprehensive global Positioning, Navigation, and Timing (PNT) services. With the full constellation now in place, users around the world can benefit from advanced accuracy and reliability in their navigation and timing applications. Due to the compatibility of BDS-3 with GPS L1 signals, information transfer between CYGNSS and BDS-3 satellites was achieved. This confirmed the performance capabilities of BDS-3 in this field, allowing for at least a twofold increase in GNSS+R measurement quantities through GPS and BDS-3 reflected signals. Despite the low acceptance of BeiDou reflected signals in various fields, their application demonstrates that China's GNSS+R remote sensing technology has reached a high level. However, it is important to note that the strength and structure of reflected signals can impact the detectability of BDS-3 GNSS+R signals in Earth orbit [13]. Advanced satellite-mounted equipment and continuous improvements in inversion accuracy are critical for positioning China's GNSS+R technology among the world's leading remote sensing capabilities.

4. Prospects and Challenges of GNSS+R Applications

Due to its operation in the L-band and its wide-ranging and all-weather capabilities, GNSS+R technology has notable advantages over traditional methods for large-scale sea wind monitoring. GNSS signals can penetrate cloud cover, enabling continuous high-resolution monitoring of sea surface wind conditions. The principles of GNSS+R originate from space-based satellites, making it more prominent in terms of real-time data transmission compared to other measurement methods, which is particularly useful in meteorological forecasting and ocean disaster monitoring. Additionally, GNSS+R data can be combined with other data sources benefiting in boosting the measurements accuracy and inversion results. However, in the development of GNSS+R, signal interference and the accuracy of inversion algorithms remain persistent challenges. Existing solutions, such as multipath effect mitigation, improved antenna design, and data fusion techniques, have been explored. However, achieving higher inversion accuracy necessitates the development of new, more precise inversion algorithms in future research. Additionally, machine learning and artificial intelligence are poised to play a crucial role in enhancing data acquisition and analysis in GNSS+R applications. The integration of AI into data processing and analysis will be a determining factor in whether GNSS+R can effectively broaden its applications in offshore wind measurement.

5. Conclusion

GNSS+R utilizes the delay between direct and reflected signals to invert characteristics and roughness of the surface by considering geometric relationships. Inversion technology is crucial for GNSS+R measuring the wind. In the GNSS+R system, the principle for retrieving wind speed relies on the positive correlation between sea surface roughness and the strength of energy of the reflected signal. By analyzing the energy variation of the reflected echo signals, sea surface wind speed can be effectively estimated, thereby enhancing measurement accuracy. And improving the precision of inversion techniques is the most direct way to enhance wind measurement accuracy.

Currently, GNSS+R is rapidly advancing worldwide. Satellites such as Europe's TechDemoSat-1, the United States' Cyclone Global Navigation Satellite System, and China's Fengyun-1A and 1B satellites, along with the BeiDou system, have all contributed to the development of GNSS+R applications in ocean wind measurement. Internationally, China’s GNSS+R technology has been advancing, and needs further improvements in sea wind detection accuracy.

GNSS+R provides significant advantages for monitoring sea surface winds. Operating in the L-band enables widespread, all-weather monitoring and delivers continuous high-resolution data, which is crucial for meteorological forecasting and marine disaster monitoring. Additionally, future integration with other data sources can enhance measurement accuracy. However, challenges remain, particularly regarding signal interference and the precision of inversion algorithms. While solutions like multipath effect suppression and improved antenna design exist, ongoing innovation is essential to further enhance inversion accuracy.

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