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Research on Key Technologies and Applications of GNSS-R Sea Surface Altimetry and Eddy Detection

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ABSTRACT

The global detection of ocean eddies is typically conducted using satellite remote sensing of sea surface height data, combined with eddy kinetic energy fields and flow fields to identify eddy centers and radii, which is crucial for climate monitoring and resource development. Ocean eddies, as circulation structures with dynamic effects, have evolution and dissipation processes that are closely related to variations in sea surface height. Global Navigation Satellite System-Reflectometry (GNSS-R), with its advantages of short revisit periods and extensive coverage, has increasingly become an efficient method for measuring sea surface height. However, factors such as sea state and satellite orbit introduce challenges in achieving precise sea surface height measurements, while the indistinct boundaries of oceanic eddies further complicate accurate eddy contour identification. To address these challenges, this thesis proposes a GNSS-R-based sea surface height measurement method. First, the along-track sea surface height for each reflection event is obtained. Then, the along-track data is processed through gridding to generate a daily mean sea surface height map. Finally, eddy height features are utilized to extract ocean eddy information from this map. This study utilized GNSS-R altimetry results to detect eddies and validated the effectiveness of the proposed method based on spaceborne measured data and simulated Asymmetric Constant Envelope Binary Offset Carrier (ACE-BOC) high-bandwidth signals, providing crucial support for global ecological and environmental protection. The main contributions and innovations of this thesis are as follows:

(1) In along-track sea surface height measurement, high wind and waves increase surface roughness, enhancing the incoherent components of the signal. This leads to the divergence of the Doppler Delay Map (DDM) power distribution at the receiver, preventing the determination of the signal propagation path based on the maximum power position and ultimately reducing the measurement accuracy. To address this issue, this paper proposes an along-track height measurement method based on dynamic multi-order feature capture of DDM. First, a multi-order feature extraction method for DDM is designed, leveraging the multi-angle time-frequency localization characteristics of the fractional Fourier transform to achieve multi-order time-frequency domain representation of DDM, thereby improving the separation of signal and noise. Second, to dynamically capture key features from the reconstructed DDM, satellite positions, and other heterogeneous information, a deformable convolution mechanism is introduced to flexibly adjust convolution sampling positions, enhancing the ability to extract local features from power-divergent DDM under high wind and wave conditions. Validation on real CYGNSS datasets demonstrates that the proposed method achieves a root mean squared error (RMSE) of 0.29 meters, representing a 26.46% improvement over traditional methods. Additionally, using high-bandwidth ACE-BOC signals, the measurement accuracy reaches 0.11 meters, an improvement of 21.43%.

(2) In the gridding process of along-track sea surface height measurement results, variations in wind speed and satellite orbital geometry lead to discrepancies in measurement accuracy within grid cells, resulting in grid-induced accuracy distortion. To address this issue, this paper proposes a time-series adaptive perception-based sea surface height gridding method. First, leveraging the orbital characteristics of multi-source satellite platforms, a multi-dimensional sea surface representation model is designed, modeling

sea surface height variations as uniform linear and uniformly accelerated nonlinear processes. This approach introduces richer representation parameters, reducing the model's sensitivity to isolated anomalies. Second, a multi-model interaction framework is established, where grid time-series correlations are analyzed to dynamically adjust model weights. This multi-model fusion strategy applies an accuracy-weighted approach to mitigate the impact of low-precision data on the overall grid results, providing a more precise depiction of sea surface height within each grid cell at any given moment. The proposed method is validated using data from CYGNSS and Fengyun-3E satellite platforms, generating high-precision global daily mean gridded sea surface height for an entire year. The RMSE of real BPSK signal measurements is 6.01 cm, representing a 38.51% improvement over traditional methods. When applying high-bandwidth ACE-BOC signals, the RMSE is further reduced to 1.11 cm, yielding a 31.25% enhancement.

(3) In the process of detecting eddies using global daily mean sea surface height maps, high temporal resolution methods are required to describe the dynamic characteristics of eddies for continuous detection. Additionally, the dense distribution of eddies leads to blurred boundaries, making precise segmentation of individual eddies challenging. This paper first validates the effectiveness of GNSS-R technology for ocean eddy detection and further proposes a fine-grained eddy detection method based on local shape feature extraction. Specifically, GNSS-R-derived global daily mean sea surface height data is utilized for daily eddy detection. A Bessel function-based eddy feature extraction technique is then applied, leveraging its localized properties to focus on eddy boundary regions and extract edge details by capturing the gradient direction variation rate. Meanwhile, a combination of edge-closed curves and local height features is used to accurately estimate the eddy center. Furthermore, based on geostrophic flow theory, surface ocean current velocity and eddy kinetic energy fields are derived, and eddy contours are refined using kinetic energy field corrections, completing the eddy detection process. Experimental results demonstrate that GNSS-R technology enables high-resolution daily eddy detection. When employing high-bandwidth ACE-BOC signals, the detection accuracy for cyclonic and anticyclonic eddies reaches 85.94% and 84.34%, respectively, representing improvements of 7.47% and 6.00% over traditional global feature extraction methods.

Finally, a spaceborne GNSS-R sea surface height measurement platform is designed. The hardware component adopts an FPGA+ARM architecture to enable efficient acquisition of reflected signals, while the software component integrates the proposed algorithms and is developed using the Vue and Django frameworks. This platform provides robust engineering support for global oceanic research.

Key words: Spaceborne GNSS-R, sea surface height measurement, ocean remote sensing, multi-source fusion, ocean eddi