Journal of Global Positioning Systems

Vol. 22, Issue 01: 173-174

Research on High-Precision Sea Surface Altimetry Methods Based on Land-Sea-Air Multi-Platform GNSS-R

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Defense date: September, 2026

Abstract

Sea surface height (SSH) is fundamental data in geodesy and marine environmental dynamics, which is widely applied to marine gravity field modeling, tidal and ocean current model establishment and other researches. Nevertheless, existing sea surface altimetry technologies fail to satisfy practical application requirements including low cost, stable observation and flexible networking. Traditional tide gauges impose strict construction conditions and high costs, making large-scale dense deployment difficult. Satellite altimetry is limited in temporal and spatial resolution and performs poorly in coastal areas. Buoy devices are susceptible to ocean currents and difficult to maintain. As an emerging remote sensing technology, Global Navigation Satellite System-Reflectometry (GNSS-R) utilizes abundant free and all-weather GNSS signals for sea surface observation. It features low equipment cost, flexible layout and large-scale networking capability, and can acquire sea surface height data with high temporal and spatial resolution. At present, single-antenna GNSS-R sea surface altimetry has been extensively studied yet suffers low temporal resolution of observations. Although dual-antenna GNSS-R altimetry can acquire continuous observations, it still faces numerous challenges such as massive data volume, heavy computational load, difficult real-time processing, insufficient long-term observation experiments, limited measurement accuracy and inadequate researches on dynamic platforms. In response to the above problems, this paper conducts systematic research on multi-platform dual-antenna GNSS-R sea surface altimetry experiments and high-precision altimetry algorithms. The main works include establishing a GNSS-R sea surface altimetry system to realize long-term real-time sea surface height monitoring on shore-based platforms, proposing high-precision altimetry algorithms based on new-generation signals, and verifying the effectiveness of GNSS-R sea surface altimetry via airborne and shipborne experiments.

The main innovations and research contents are

summarized as follows:

1. To mitigate excessive data volume and computational overhead that hinder real-time processing under the dual-antenna architecture, two customized GNSS-R sea surface height monitoring systems are developed to realize real-time code-delay altimetry utilizing multi-constellation GNSS signals and real-time output of carrier-phase observables respectively. The code-delay-based system supports concurrent processing of BDS B2a, GPS L5 and QZSS L5 signals, with field tests verifying its real-time operational capability and altimetry performance. The carrier-phase-oriented signal processing system processes GPS L1 signals and outputs in-phase/quadrature samples and raw carrier-phase data in real time; when coupled with post-processing algorithms, the system holds promising potential for real-time carrier-phase altimetry.

2. To fill the research gap of long-duration continuous observation campaigns, the proposed monitoring systems are deployed to conduct long-term shore-based dual-antenna GNSS-R code-delay altimetry. Two one-month shore-based field experiments are carried out using the code-delay altimetry system: the root-mean-square error (RMSE) of multi-constellation altimetry results for BDS, GPS and QZSS reaches 11.9 cm, 13.7 cm and 23.5 cm separately, whereas standalone QZSS altimetry achieves an RMSE of 9.7 cm. When the carrier-phase processing system is combined with post-processing strategies, resultant altimetry attains an RMSE of 3.5 cm, which validates the feasibility of real-time carrier-phase GNSS-R sea surface altimetry.

3. Aiming to improve the limited accuracy inherent to conventional GNSS-R code-delay altimetry, a novel wideband pseudorange combination algorithm is proposed to refine code-based altimetry precision. The algorithm implements joint tracking of paired signals including BDS B2a/B2b and Galileo E5a/E5b, followed by frequency shifting to synthesize composite B2 and E5 wideband signals. Free from high-bandwidth receiver requirements for raw data acquisition, this method establishes a universal processing framework for efficient exploitation of wideband BDS and Galileo signals. Unmanned Aerial Vehicle (UAV) -borne experiments demonstrate that the proposed approach improves B2 and E5 code-delay altimetry precision by up to 60.2% and 45.7%, respectively.

4. To resolve unstable phase tracking-induced accuracy degradation in GNSS-R carrier-phase altimetry, a subcarrier-based GNSS-R altimetry method is put forward to enhance the stability and precision of phase-based measurements. This algorithm jointly tracks B2a/B2b and E5a/E5b components to construct virtual B2 and E5 composite signals, from which corresponding subcarrier observables are extracted for sea surface height inversion. UAV-borne validations confirm stable phase tracking throughout observation, delivering an overall altimetry RMSE of 5.8 cm.

5. In response to scarce existing studies and field trials on dynamic observation platforms, airborne and shipborne GNSS-R altimetry experiments are implemented to demonstrate the practicability of GNSS-R altimetry under high-dynamic environments. Dual-antenna airborne GNSS-R campaigns are organized, and code-delay altimetry outcomes are analyzed to characterize the performance of airborne GNSS-R altimetry. Two cruise-based field experiments are designed based on dual-frequency carrier-phase altimetry theory, and high-precision shipborne altimetry results are acquired, verifying the great prospect of shipborne carrier-phase GNSS-R altimetry.

Key words: GNSS Reflectometry, Sea surface height altimetry, Dual-antenna GNSS-R, Code delay, Carrier phase, GNSS-R receiver