

Simulation of Spaceborne Scatterometer Systems for Tropical Cyclone Observation

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Introduction

Spaceborne scatterometers are active microwave remote sensing instruments designed to quantify Earth's surface backscattering coefficients σ^0 (NRCS) for geophysical parameter retrieval[1]. Their primary application is ocean surface wind vector observation, achieved by transmitting microwave pulses toward the sea surface and recording the backscattered echoes modulated by sea surface roughness, which is mainly influenced by local wind fields. The wind speed and direction are subsequently retrieved through retrieval algorithms, such as the maximum likelihood estimation (MLE) method combined with geophysical model functions (GMFs).

Operational spaceborne scatterometers are primarily categorized into three observation architectures based on beam patterns and scanning modes, as illustrated in Fig. 1:

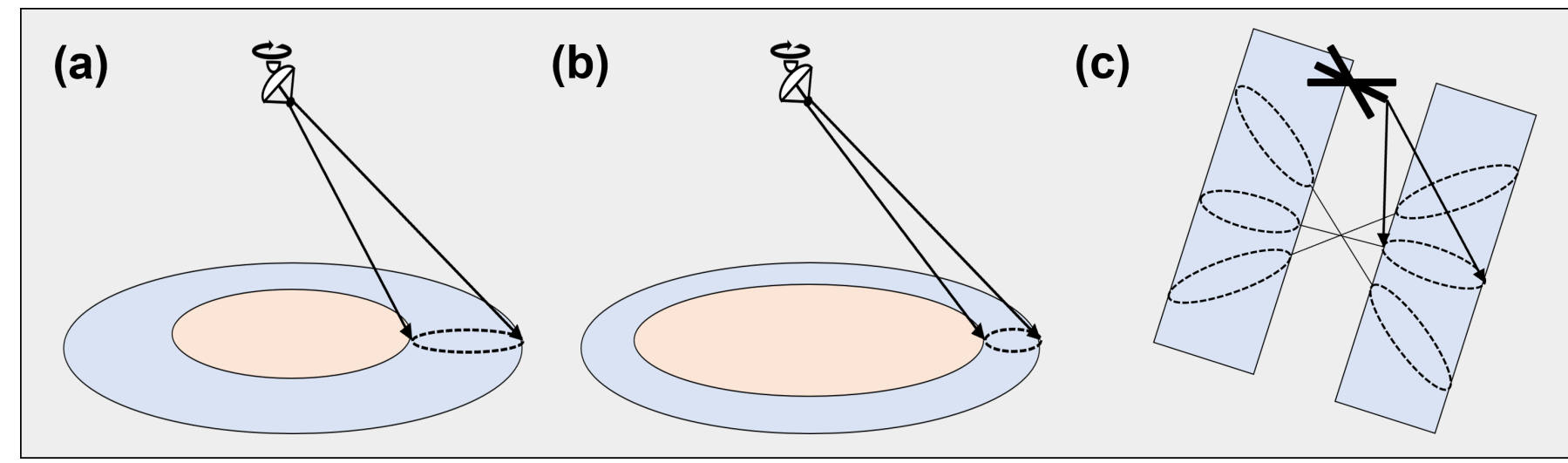


Fig. 1: Observation Geometries of Three Scatterometer Systems

(a). **Rotating Fan-beam Scatterometers** utilize fan beams with wide-range coverage in the along-track dimension, enabling lower rotation speeds that significantly increase independent samples per target while maintaining full swath coverage. (b). **Rotating Pencil-beam Scatterometers** employ narrow antenna beams with small footprints in both azimuth and range directions. Their high rotational scanning speed ensures continuous swath coverage without blind zones, but this configuration yields fewer independent samples per target due to rapid beam scanning. (c). **Fixed fan-beam scatterometers**, such as ASCAT deploy multiple fixed beams (fore, mid, and aft) that scan through satellite motion. This design achieves comparable independent samples to rotating fan-beam systems.

Tropical cyclones (TCs) are among the most disastrous natural events, where high-quality wind field observations are critical for both scientific research and operational application. Among the existing TC observation methods, scatterometer demonstrates unique advantages by providing large spatial scale, simultaneous wind speed/direction measurements within short duration. Recent studies have developed solutions to key TC observation challenges, including extreme wind retrieval and precipitation contamination, significantly expanding scatterometers application potential[2,3].

Objective & Method

To systematically evaluate scatterometer performance for tropical cyclone (TC) observations across three operational systems: rotating pencil-beam, rotating fan-beam, and fixed fan-beam systems, Our study establishes a end-to-end simulation framework. The accuracy of backscattering coefficient measurements and wind retrieval were simulated under different wind speeds, and then the TC observation performance was simulated using reanalysis data from TC cases in the northwest Pacific.

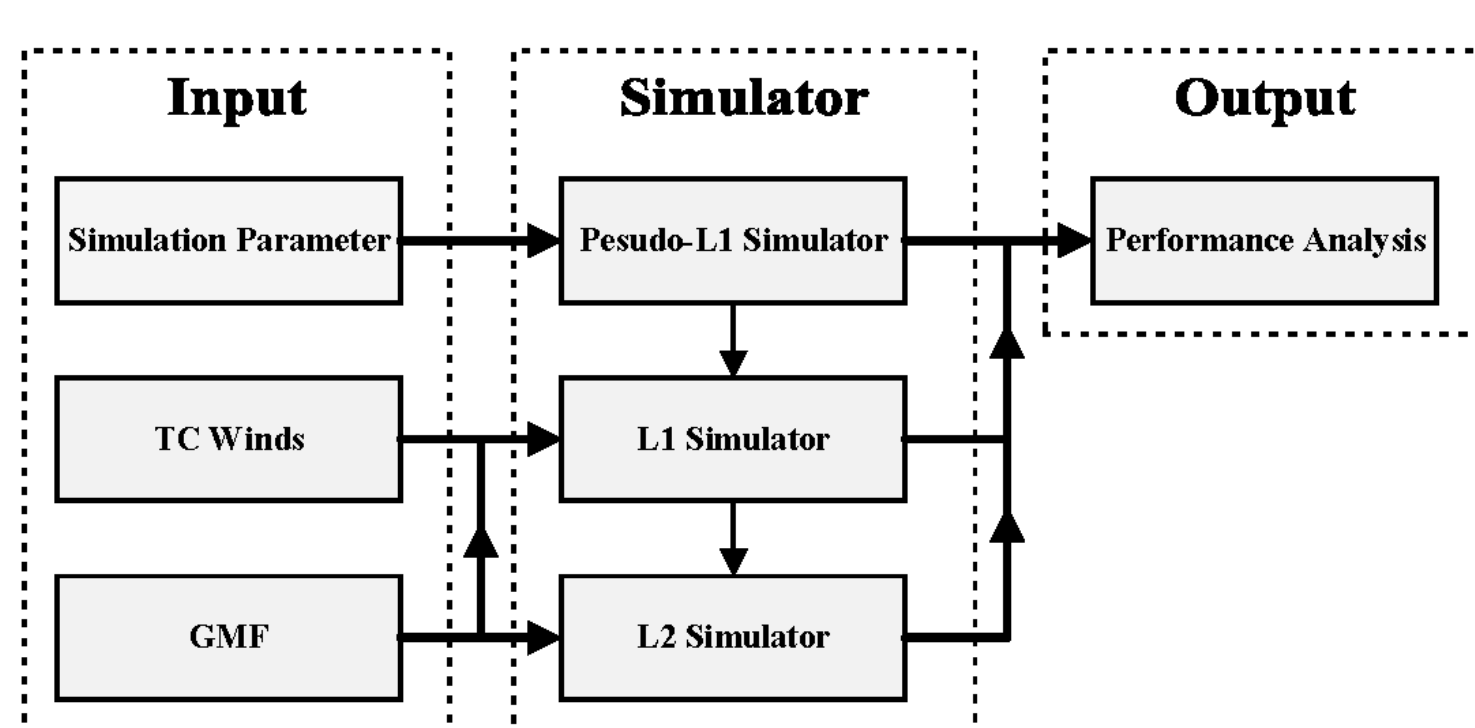


Fig. 2: Scatterometer System Simulation Model

The simulator's core is the Pseudo-L1 Simulator module, which generates observation geometry and wind-field-independent intermediate results for backscattering coefficient simulation. These outputs feed into the L1 Simulator module that combines them with GMFs to simulate backscattering coefficient observations, incorporating normally distributed noise whose normalized standard deviations are derived from operational scatterometer data. The L2 Simulator module then performs wind field inversion from the simulated backscattering coefficients using MLE algorithms, with wind directions determined by circular median filtering. Finally, the Performance Analysis module evaluates the scatterometer's observational performance based on these simulations and retrieval results.

NRCS measurement metric[4]:(scatterometer system error K_{pc})

$$K_{pc} = \sqrt{\frac{1}{N_{\text{samples}}} \left(1 + \frac{1}{SNR' \cdot \sigma^0}\right)^2 + \frac{1}{N_{\text{noise}}} \left(\frac{1}{SNR' \cdot \sigma^0}\right)^2}$$

Where: N_{samples} is the Independent samples, SNR' is the normalized signal-to-noise ratio, N_{noise} is the noise measurement samples and independent of the target.

High wind speed conditions: (larger NRCS)

$$K_{pc} \approx \sqrt{\frac{1}{N_{\text{samples}}}}$$

Independent sample N_{samples} dominates NRCS measurement error.

low wind speed conditions: (smaller NRCS)

$$K_{pc} \approx \sqrt{\left(\frac{1}{N_{\text{samples}}} + \frac{1}{N_{\text{noise}}}\right) \cdot \left(\frac{1}{SNR' \cdot \sigma^0}\right)}$$

Both the N_{samples} and the SNR' affect measurement error.

Results

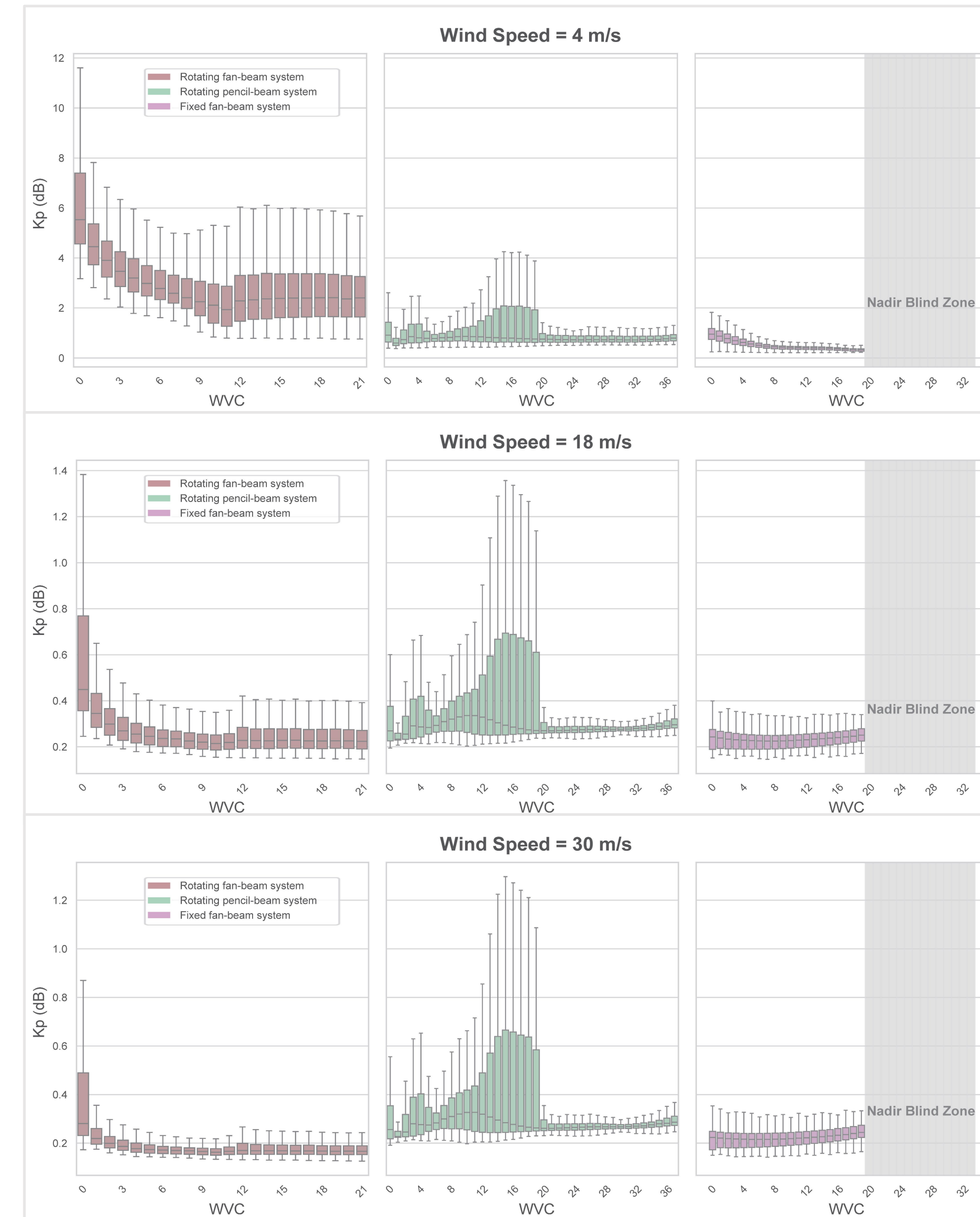


Fig. 3: K_{pc} of Backscattering Coefficient Measurements Under Different Wind Speed.

Low winds (4 m/s): Rotating pencil-beam and fixed fan-beam systems achieve superior NRCS accuracies with $K_{pc} < 1$ dB and wind speed RMSE < 0.5 m/s in the sweet swath, while rotating fan-beam systems demonstrate degraded performance with $K_{pc} < 4$ dB and wind speed RMSE 0.6–2.0 m/s.

Moderate winds (18 m/s): Rotating Pencil-beam system maintain NRCS accuracy with $K_{pc} < 0.6$ dB in the sweet swath and marginally reduced at far edges, and wind speed RMSE < 1.0 m/s, whereas both fan-beam systems deliver enhanced performance with $K_{pc} < 0.4$ dB, wind speed RMSE < 0.5 m/s.

High winds (30 m/s): Both Fan-beam systems excel with a NRCS accuracy around 0.2 dB and wind speed RMSE < 1.5 m/s, while rotating pencil-beam systems exhibit spatial variability with NRCS accuracy from 0.3 dB to 0.6 dB across the whole swath and higher wind speed RMSE < 2.8 m/s.

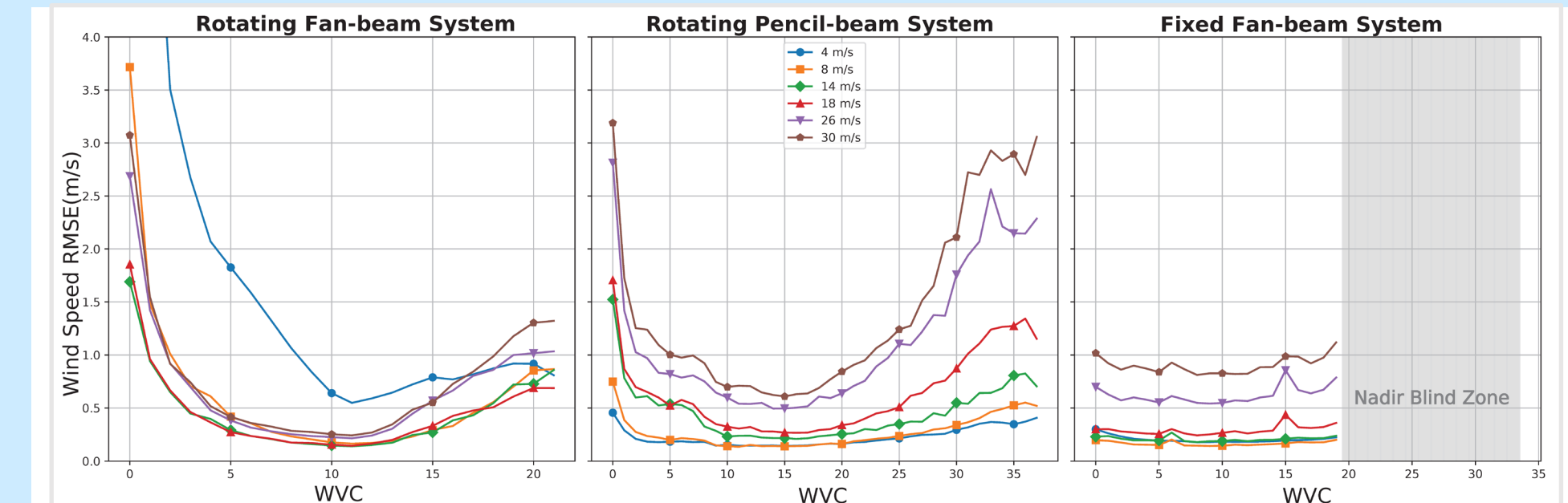


Fig. 4: Wind Speed RMSE Under Different Wind Speed.

Analysis of the Northwest Pacific tropical cyclone observation simulation in Fig. 5 reveals that the fan-beam systems yield better retrieval precision, where the rotating and fixed fan-beam systems are more effective in observing the high wind structures near the eye wall, while the rotating pencil-beam system is more accurate in observing structures with relatively lower wind speeds. These phenomena are consistent with the analysis of backscattering coefficient measurement accuracy in Fig. 3 and wind speed RMSE in Fig. 4, which further demonstrates the high accuracy of the fan-beam systems for TC observations.

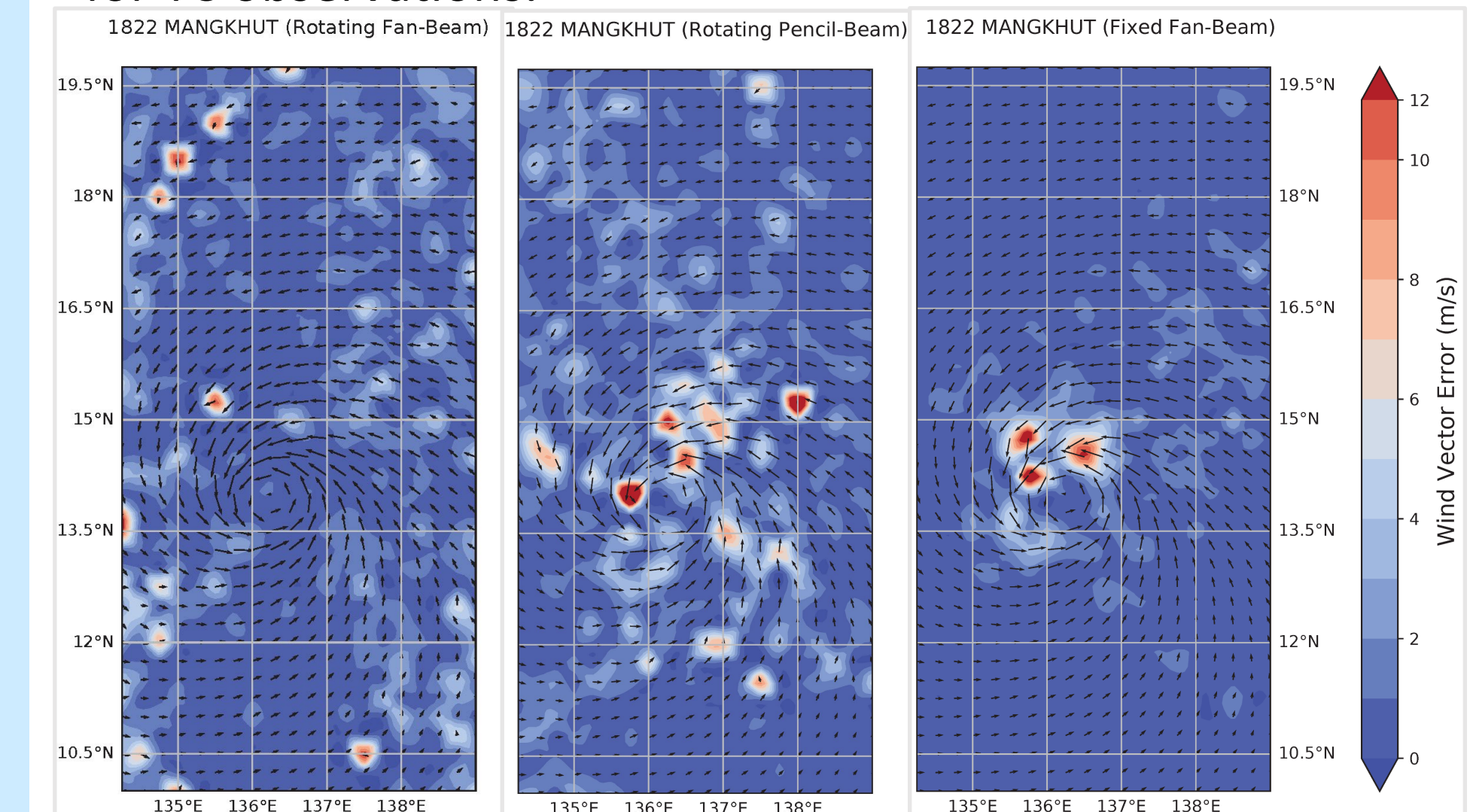


Fig. 5: Wind Vector Errors of TC Case (1822 MANGKHUT)

Conclusion & Discussion

In this study, tropical cyclone observations were simulated and the observation performance of the rotating pencil-beam scatterometer, the rotating pencil-beam scatterometer and fixed fan-beam scatterometer were analyzed. Compared to rotating pencil-beam system, rotating fan-beam system and fixed fan-beam system benefit from their sampling advantage in each view, and therefore obtain better accuracy in wind retrieval under the extreme wind conditions. In addition, compared with fixed fan-beam system, rotating pencil-beam system and rotating fan-beam system have no nadir blind zone and larger swath, which contribute to improved spatial coverage for TC observation.

Building on the established simulation model, future study will focus on two key improvements: (1). the incorporation of real observation geometry parameters to improve the fidelity of the simulation, (2). the consideration of environmental factors such as precipitation rates, and (3). the low incidence observation simulation. These extended approaches will allow for a more comprehensive assessment of performance under TC conditions.

Key Reference

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