14TH IEEE INTERNATIONAL CONFERENCE ON WIRELESS
FOR SPACE AND EXTREME ENVIRONMENTS - WISEE 2026
THE IEEE WIRELESS IN SPACE AND EXTREME ENVIRONMENTS CONFERENCE WEBSITE

W-KAST: Predictive Optical Link-State Estimation for LEO Space-Terrestrial Networks

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1 Motivation and Research Challenges

Satellite-to-ground laser communication (SGLC) is a promising technology for providing high-capacity feeder links in future large-scale low-earth-orbit (LEO) constellation networks. However, rapidly varying propagation geometry and nonstationary atmospheric optical turbulence cause pronounced fluctuations in slant-path link quality during the limited communication windows. To support proactive link scheduling, this study reconstructs high-resolution Fried-parameter (r_0) fields for characterizing the spatially varying turbulence state and develops W-KAST for 30-min prediction of future fields.

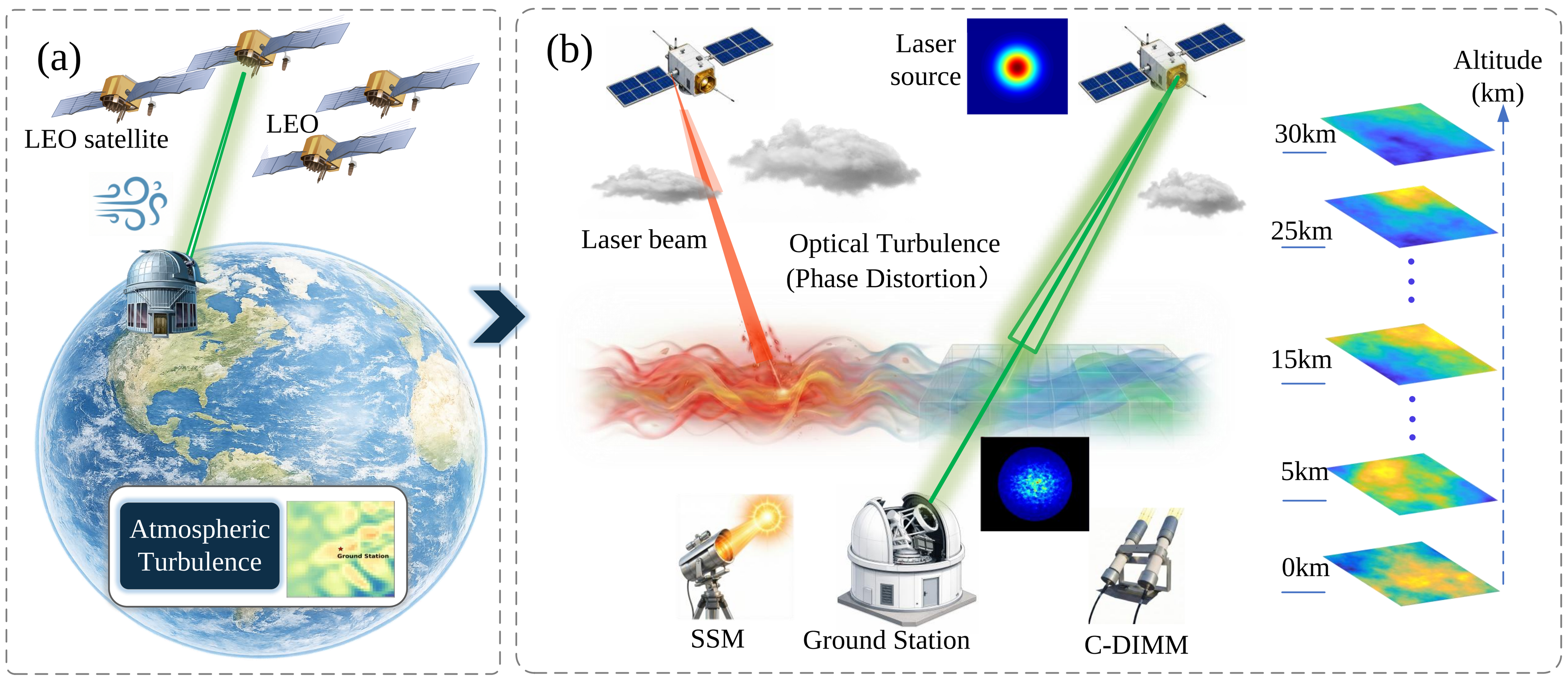

Fig. 1. System scenario and data-generation framework of W-KAST

2 Proposed W-KAST Framework

W-KAST integrates adaptive fractal-wavelet representations with Swin-based spatiotemporal modeling for short-term prediction of slant-path r_0 fields. Multi-scale wavelet responses are adaptively fused within KAN-based feed-forward modules, while local and shifted-window attention capture spatial dependencies across different scales. Historical r_0 fields are jointly encoded to extract their spatiotemporal evolution and predict the future slant-path r_0 field.

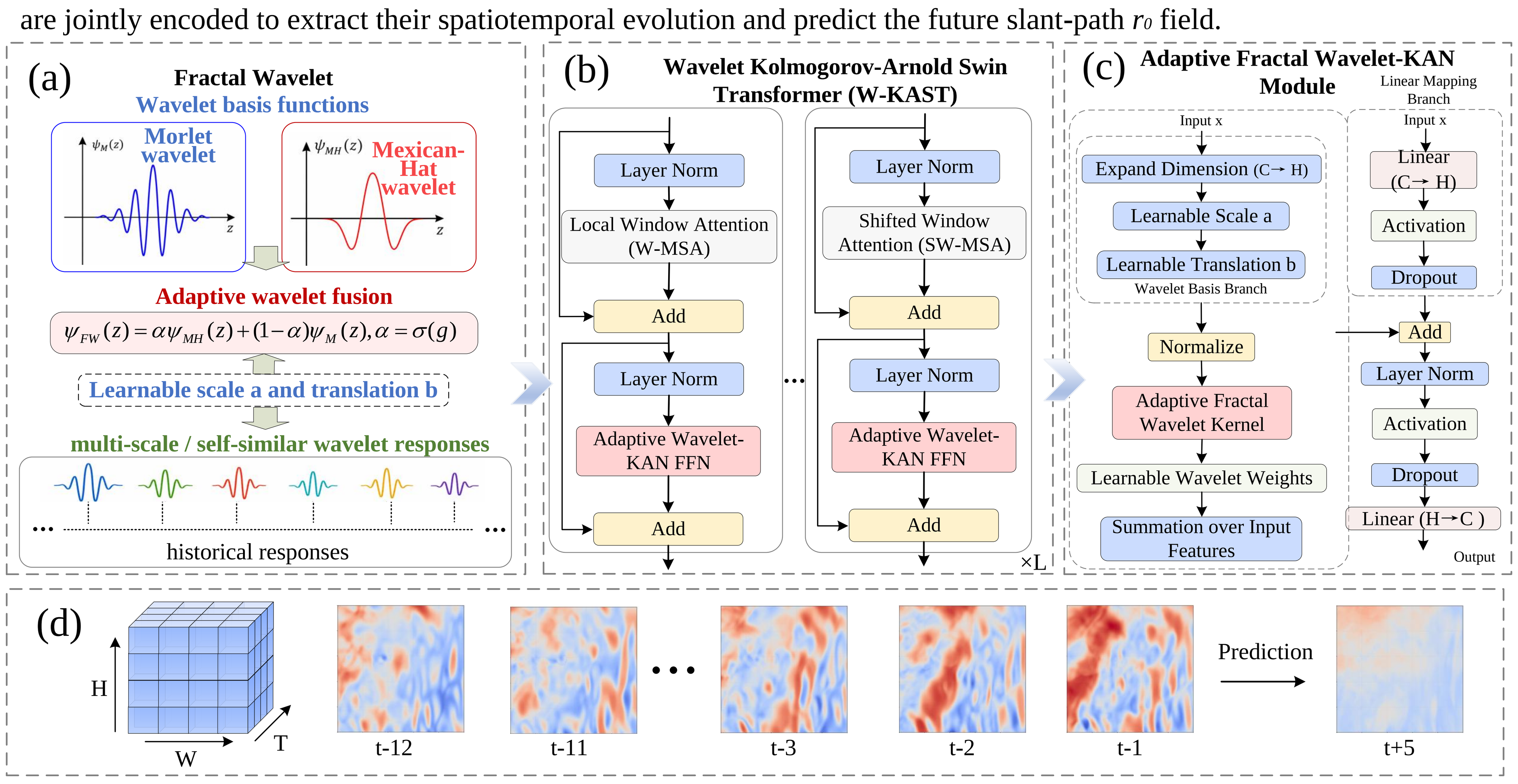

Fig. 2. Overview of the proposed W-KAST framework

3 Multi-Site Joint Experiments

Joint ground-based observation campaigns were conducted at multiple sites in Nanjing and Changchun from 2021 to 2025, providing multi-site optical-turbulence measurements for model calibration and validation.

Fig. 3. Nanjing Yingtian Applied Validation Ground Station (2021)

Changguang Satellite Applied Validation Ground Station (2024)

CIOMP Applied Validation Ground Station (2024)

Nanjing Yingtian Applied Validation Ground Station (2025)

4 Atmospheric Turbulence Reconstruction

The r_0 characterizes the path-integrated effect of optical turbulence and serves as a key indicator of turbulence strength along an optical link. GFS-driven WRF meteorological fields are used to reconstruct the three-dimensional optical-turbulence field, from which slant-path r_0 fields are derived for LEO satellite-to-ground laser links.

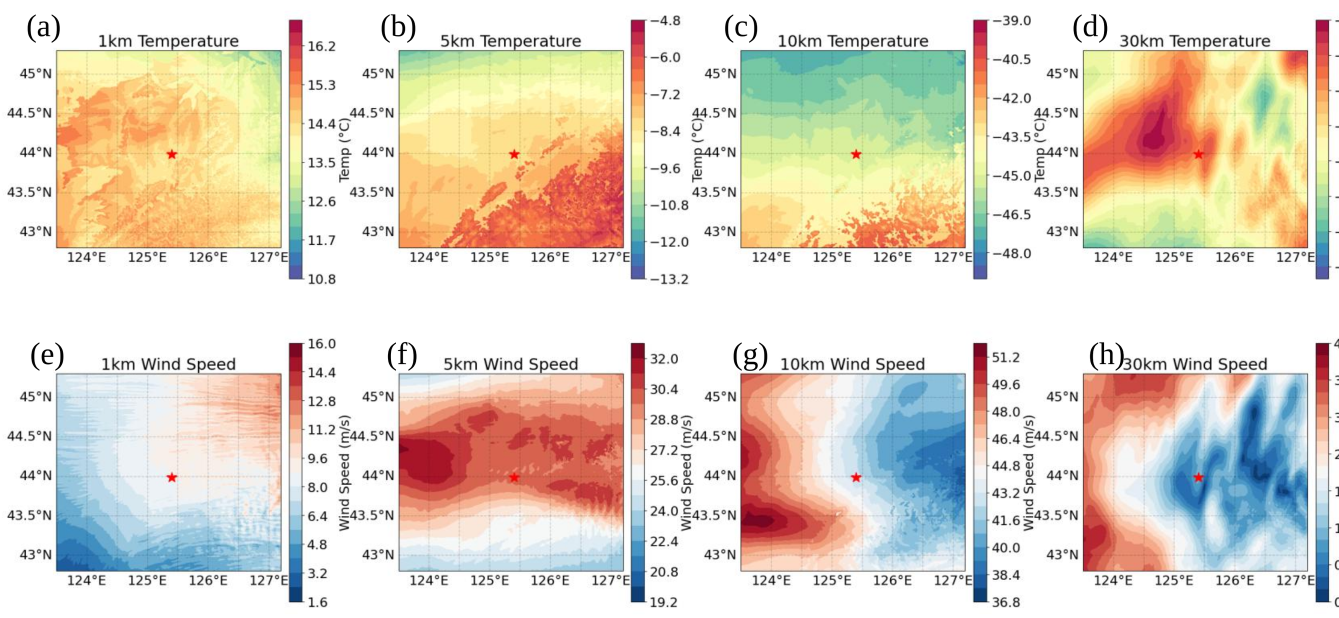

Fig. 4. Spatial distributions of temperature and wind speed at 1, 5, 10, and 30 km altitudes on September 16, 2025.

The three-dimensional refractive-index structure constant field is reconstructed to characterize the spatial distribution of optical turbulence and derive the slant-path r_0 through path integration.

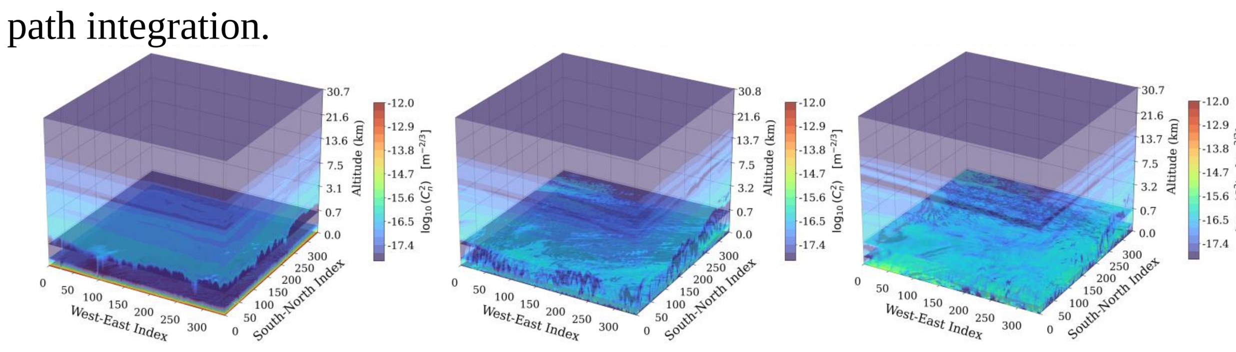

Fig. 5. Three-dimensional distributions of the atmospheric refractive-index structure constant on September 16, 2025.

5 Observation-Constrained Calibration

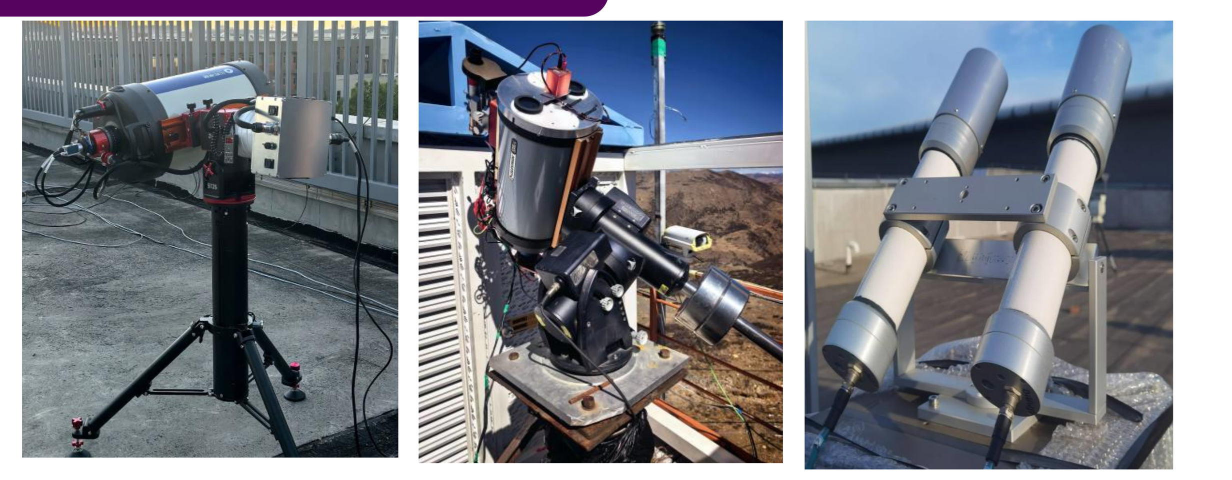

Fig. 6. Representative ground-based optical-turbulence monitoring instruments used in the joint observation campaigns.

Daytime S-DIMM and nighttime DIMM observations are used to calibrate the WRF-derived r_0. The observation-constrained r_0 fields reproduce the measured diurnal evolution and provide consistent daytime-to-nighttime transitions.

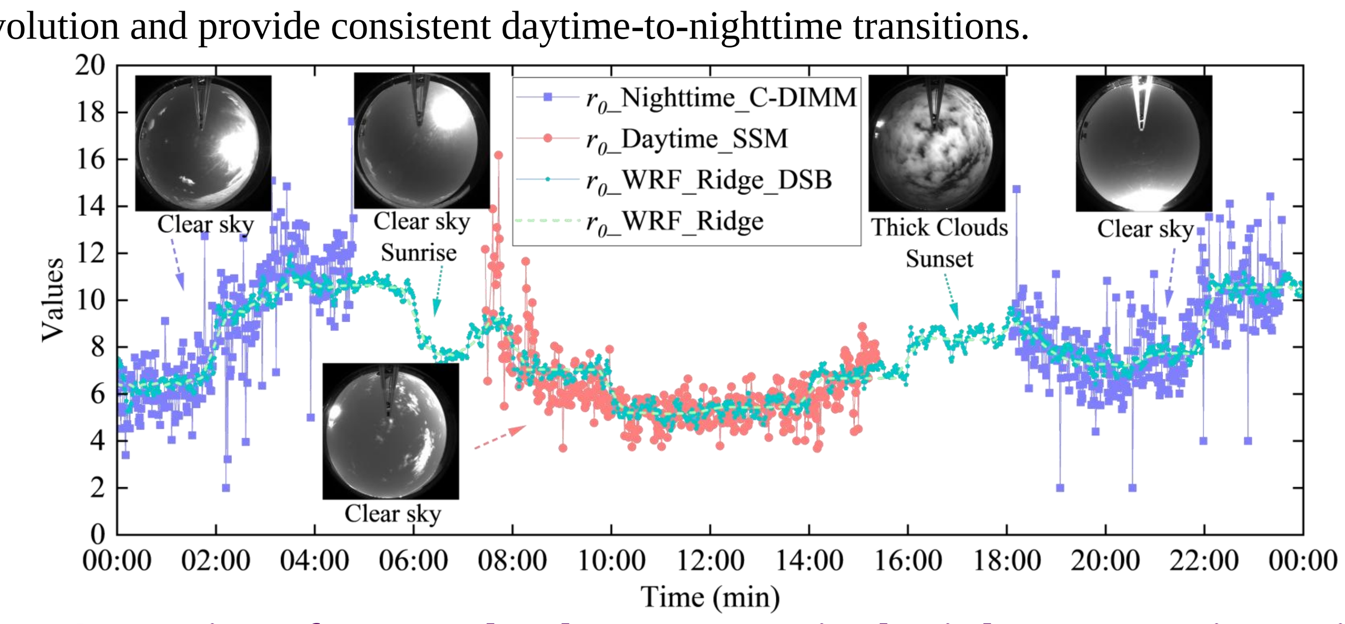

Fig. 7. Comparison of measured and WRF-constrained Fried-parameter time series on September 16, 2025, with representative sky conditions indicated throughout the day.

W-KAST preserves the spatial structure of the slant-path r_0 field, with 30-min prediction errors remaining spatially localized across both zenith-angle domains.

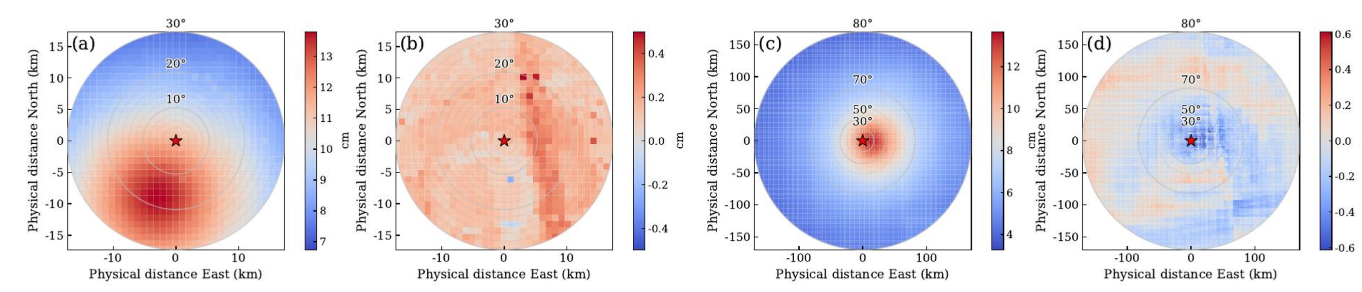

Fig. 8. Reference slant-path equivalent Fried-parameter fields and corresponding 30-min prediction errors.

6 Results and Performance Evaluation

W-KAST achieves the lowest MAE across all eight season–angle settings, with macro-averaged MAEs of 0.2197 and 0.1571 cm over the 0°~30° and 0°~80° zenith-angle ranges, respectively. Relative to persistence, W-KAST reduces the 30-min prediction MAE by 57.1% and 66.9% over the corresponding ranges, respectively.

Table. 1. 30-min prediction MAE across seasons and zenith-angle ranges

Season	W-KAST		KAT		Swin		KAN		U-Net		ConvLSTM		GWN	
	0°–30°	0°–80°	0°–30°	0°–80°	0°–30°	0°–80°	0°–30°	0°–80°	0°–30°	0°–80°	0°–30°	0°–80°	0°–30°	0°–80°
Winter	0.1707	0.2253	0.2401	0.2720	0.2307	0.2753	0.3888	0.3731	0.2541	0.4032	0.1972	0.2885	0.3885	0.2783
Spring	0.2641	0.1039	0.3221	0.2231	0.2741	0.2039	0.3371	0.2687	0.2712	0.2324	0.2779	0.1511	0.3186	0.1543
Summer	0.1640	0.0955	0.2071	0.2234	0.2140	0.1955	0.2808	0.2578	0.1981	0.1268	0.1810	0.1245	0.3039	0.1384
Autumn	0.2800	0.2036	0.3020	0.3341	0.3499	0.3054	0.3895	0.3398	0.3499	0.4290	0.3269	0.3164	0.3272	0.2824
Four-period macro avg.	**0.2197**	**0.1571**	0.2678	0.2632	0.2672	0.2450	0.3491	0.3099	0.2683	0.2979	0.2458	0.2201	0.3346	0.2134

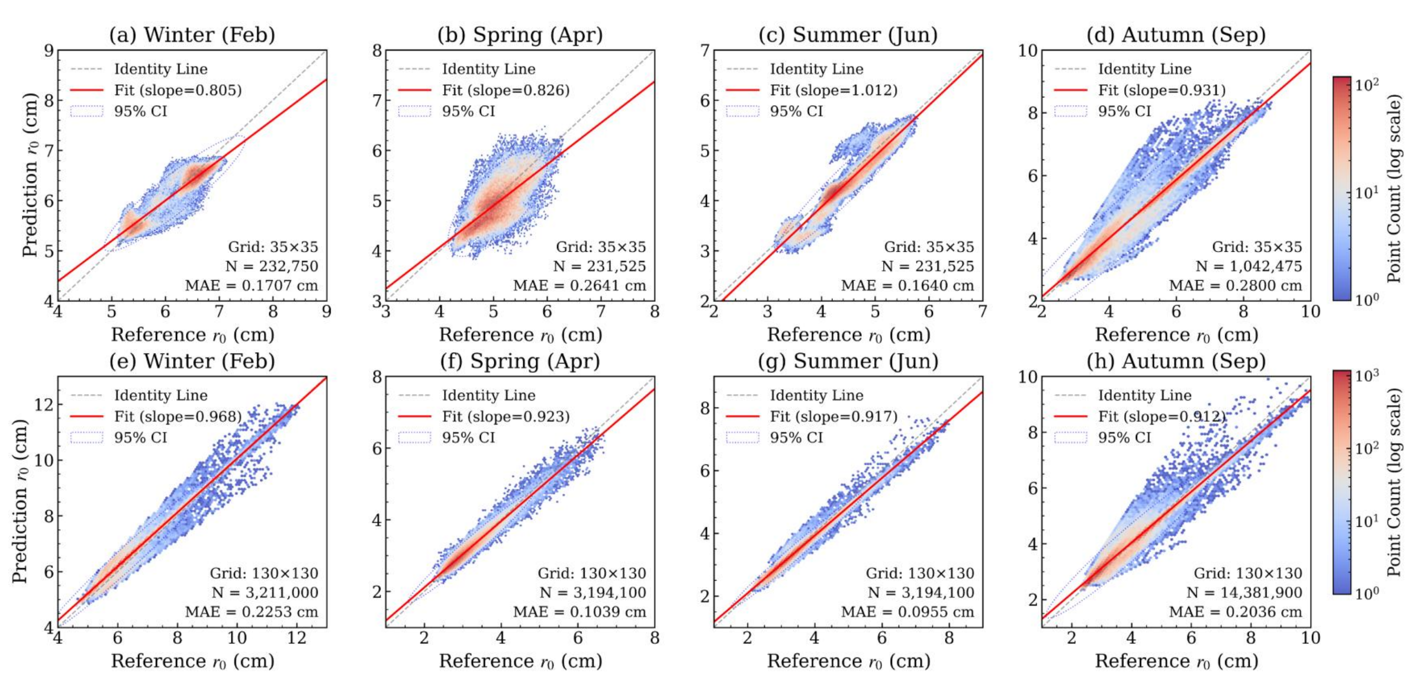

Fig. 9. Point-density scatter plots of predicted versus reference Fried parameters across four representative seasons.

Meteorological Reconstruction → Observation-Constrained Calibration → W-KAST Short-Term Prediction → Performance Evaluation and Link-State Support