Atmospheric Turbulence Mitigation in the Deep Learning Era: A Critical Review from CNNs and GANs to Transformers, Diffusion, Mamba, and Physics-Informed Models

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Abstract

Anyone who has watched a distant scene shimmer above hot pavement has seen atmospheric turbulence destroy image detail. In long-range imaging, turbulence produces spatially varying blur, geometric warping, scintillation, and temporal instability. Recovering the underlying scene is therefore an ill-posed inverse problem, and learned priors must compensate for distortions that simplified optical models capture only partially. We use turbulence mitigation as the umbrella term for all countermeasures and turbulence restoration for its computational core, the estimation of a clean image from degraded observations. From a cognitive-computing perspective, mitigation is not

merely image enhancement. It is an uncertainty-constrained visual inference problem in which an intelligent system must reconstruct, interpret, and act on observations relayed through a stochastic physical channel. This critical review examines how the deep learning era has reshaped turbulence mitigation, with physics as the foundation for understanding degradation and designing inductive biases. It traces the architectural progression from convolutional and adversarial networks to Transformers, denoising diffusion models, Mamba and other state-space architectures, and physics-informed frameworks. For each family, we ask a common question: How does it treat the aleatoric uncertainty intrinsic to a random optical channel and the epistemic uncertainty introduced by scarce and simulator-dominated training data? The review also analyzes datasets, simulation strategies, loss functions, and evaluation metrics, and it separates the small body of shared-protocol benchmark evidence from the far larger body of self-reported results that cannot be compared across studies. Persistent obstacles include the synthetic-to-real domain gap, the scarcity of paired real turbulence data, the mismatch between fidelity metrics and downstream task performance, and the computational cost that limits operational deployment. We close with an AI-centered agenda in which uncertainty quantification stands alongside domain adaptation as a first-order priority.

Author keywords

atmospheric turbulence; cognitive computing; computer vision; deep learning; diffusion model; image restoration; Mamba; physics-informed learning; Transformer; uncertainty quantification

Indexed keywords

Engineering controlled terms

Atmospheric thermodynamics; Cognitive systems; Computer vision; Diffusion; Intelligent systems; Inverse problems; Learning systems; Restoration; Stochastic systems

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Abstract

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