Maximum Likelihood Filtering for Particle Tracking in Turbulent Flows

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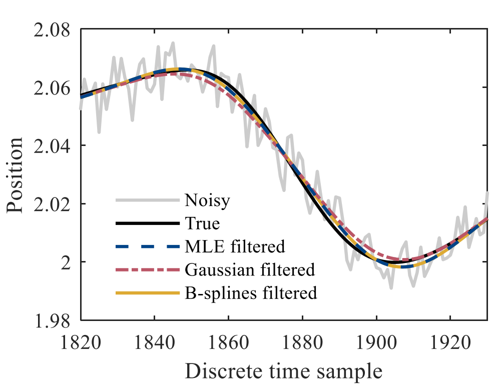
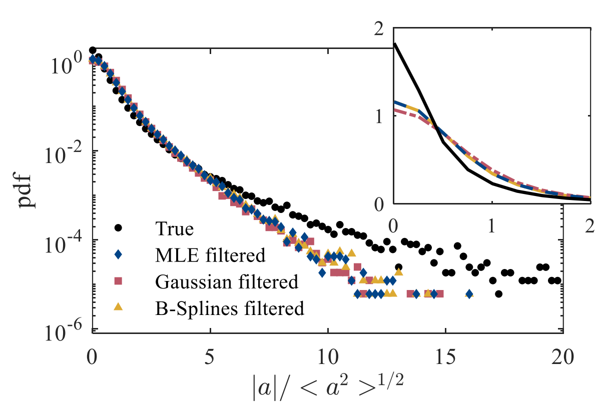
Lagrangian Particle Tracking (LPT) is a critical tool for studying turbulence, where accurately estimating particle acceleration is essential for understanding flow dynamics. However, differentiation amplifies noise, making robust filtering techniques necessary. Traditional Gaussian smoothing introduces selection bias by discarding short tracks, while B-spline filtering mitigates this issue but remains sensitive to sampling rates. Our Maximum Likelihood Estimation (MLE)-based filter leverages stochastic process modeling to provide physically consistent smoothing with reduced noise and minimal signal degradation. Our approach explicitly models measurement noise and process uncertainty, enabling a filter that adapts to different turbulence conditions. We apply our method to synthetic trajectories extracted from the Johns Hopkins Turbulence Database and compare its performance to Gaussian and B-spline filters. Our results demonstrate that the MLE filter significantly reduces both pass-through noise and signal degradation, yielding more accurate position (left figure) and acceleration statistics (right figure) compared to the Gaussian smoothing approach. The improvements in accuracy allow for a better representation of intermittent acceleration events, which are crucial for understanding small-scale turbulence dynamics. Additionally, our approach provides a robust framework for analyzing particle motion in flows with varying levels of turbulence intensity, offering a systematic way to extract reliable statistical insights from noisy measurements. While results are comparable to the B-splines approach, the MLE filter offers greater flexibility through its physics-based formulation. Unlike traditional filtering methods, which rely on heuristic parameter tuning, the MLE approach allows for principled parameter selection based on physical characteristics of the flow, enhancing its predictive capabilities. By addressing noise-related biases and improving acceleration estimates, our MLE filtering framework provides a robust alternative for LPT applications in turbulence research. Future work will extend this method to experimental data, refining stochastic process models to enhance accuracy across diverse flow conditions and exploring applications in real-world turbulent flows.





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