Maximum-Likelihood and Hamiltonian Monte Carlo Techniques to Doppler Moment Estimation for Precipitation Using Weather Radar Echoes

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On Doppler Processing for Fast Scanning Radars

***Max 3D Radar*: Robin Radar Systems B.V.**

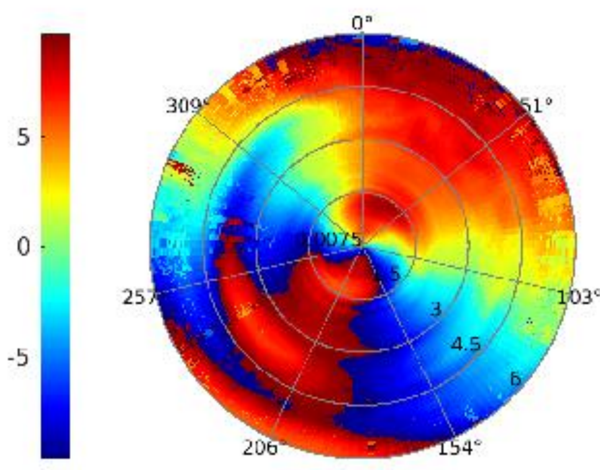
***MESEWI Radar:* TU Delft**

Typical use: Detection and tracking of weak moving point-like targets: birds and drones.
Limitation: Fast Scans result in low time on target.
Challenge: Doppler processing for extended weather objects.

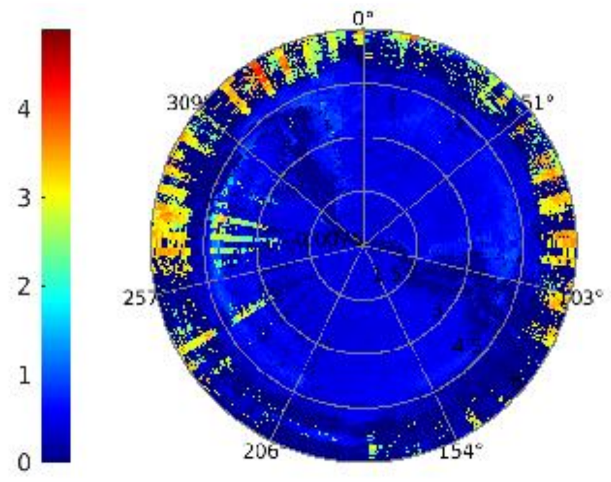
The Proposed Signal Processing Pipeline:

Step 1: Proposed ***Parametric Spectrum Estimator* (PSE)** [1]
1. Moment estimation with low time on target
2. Ability to use data from multiple scans

PhD Thesis



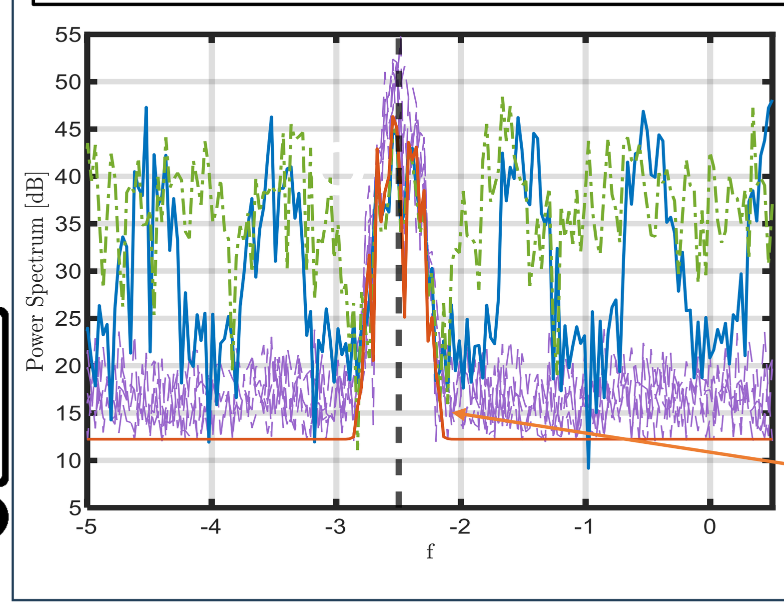
PSE

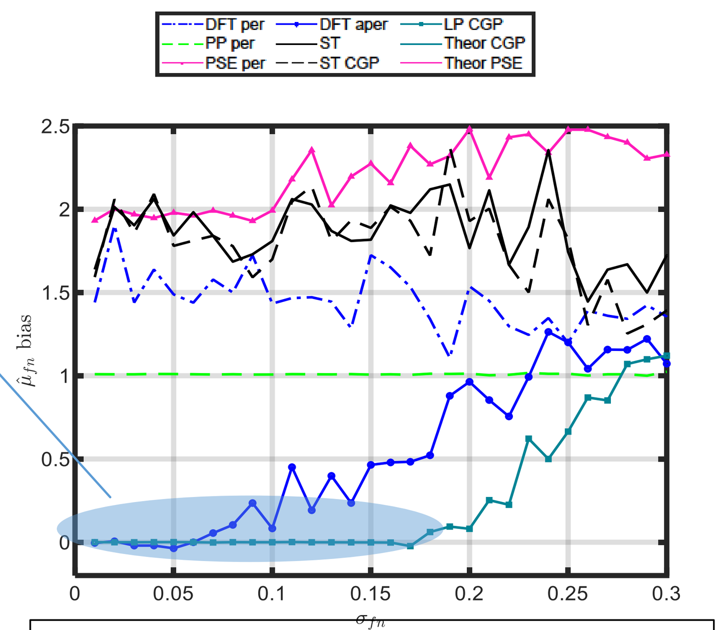


Mean Doppler Velocity | Five scans integrated | Doppler spectrum width

Step 2: Doppler counter-aliasing [2]
1. Aperiodic (Non-linear, Log-periodic) echo sequence
2. ***Complex Gaussian Process Regression* (CGP-R)** to reconstruct the signal in the frequency domain

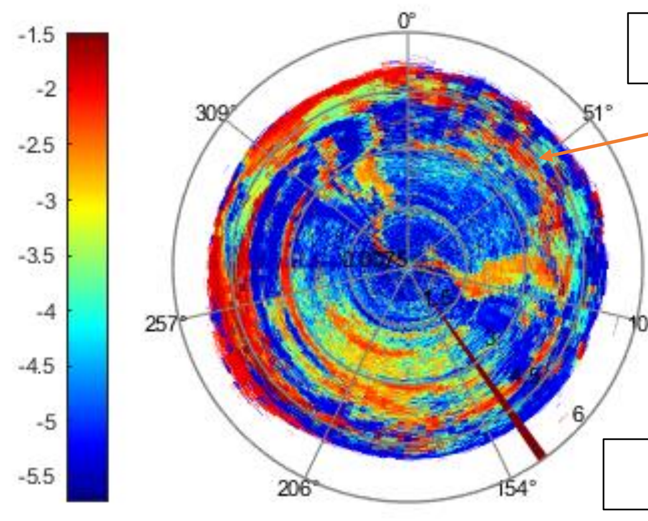
Bias: $\mathbb{B}[\hat{\theta}] = \mathbb{E}[\hat{\theta}] - \theta$: the more closer to 0, the better.
Almost zero bias with the proposed technique





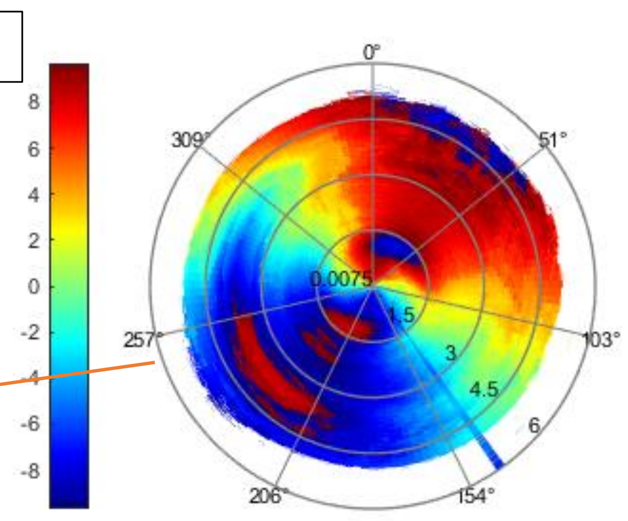
Spectrum Reconstruction
No ambiguity with the proposed approach

Step 3: Estimating Wind and Vertical fall speeds jointly from Doppler measurements [3]



Mean terminal fall

MIWESE



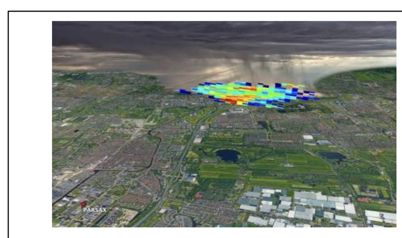
Mean radial wind

[1] T. Dash, H. Driessen, O. Krasnov, and A. Yarovoy, “Doppler Spectrum Parameter Estimation for Weather Radar Echoes Using a Parametric Semi- analytical Model,” IEEE Trans. Geosci. Remote Sens., vol. 62, pp. 1–18, 2024, doi: 10.1109/TGRS.2023.3338233
[2] T. Dash, H. Driessen, O. A. Krasnov and A. Yarovoy, "Counter-Aliasing Is Better Than De-Aliasing: Application to Doppler Weather Radar With Aperiodic Pulse Train," in IEEE Transactions on Geoscience and Remote Sensing, vol. 62, pp. 1-17, 2024, Art no. 5109017, doi: 10.1109/TGRS.2024.3438567.
[3] T. Dash, H. Driessen, O. A. Krasnov, and A. G. Yarovoy, “Joint Estimation of Raindrop Size Distribution Parameters and Wind Velocity Field Using a Fast Scanning Weather Doppler Radar,” [Submitted]

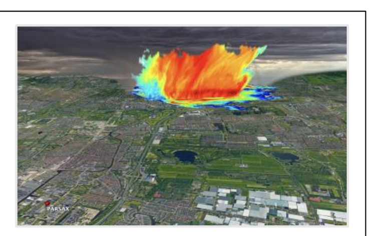
Next Generation Radar for Remote Sensing

***PH**ased **A**rray **R**adar for **A**tmospheric Research* **(PHARA)**

Instantaneous spatiotemporal evolution of storms [dynamic estimation]

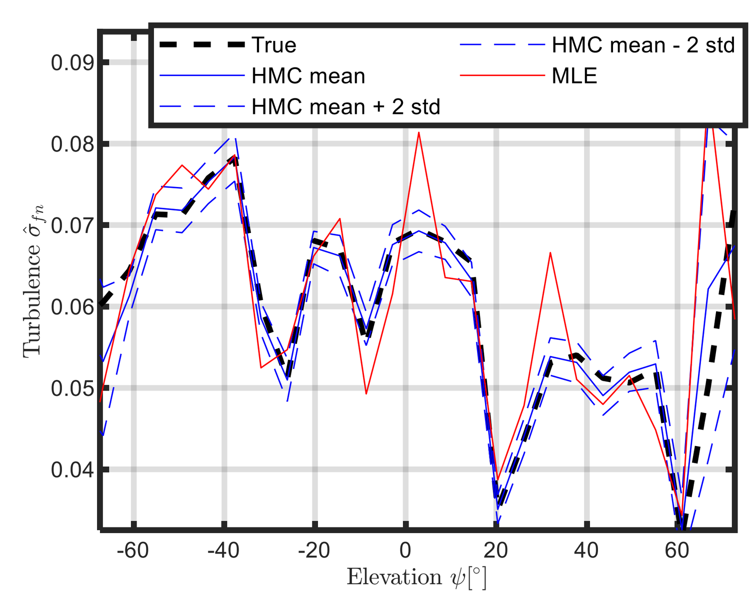


State of the art profile (2D)



Expected 3D profile from PHARA

Initial results: Dynamic Spatial Estimation [Elevation x Doppler] with Maximum Likelihood [MLE] and Hamiltonian Monte Carlo [HMC]



θ: Doppler Moments: Elevation (K) x Number of moments

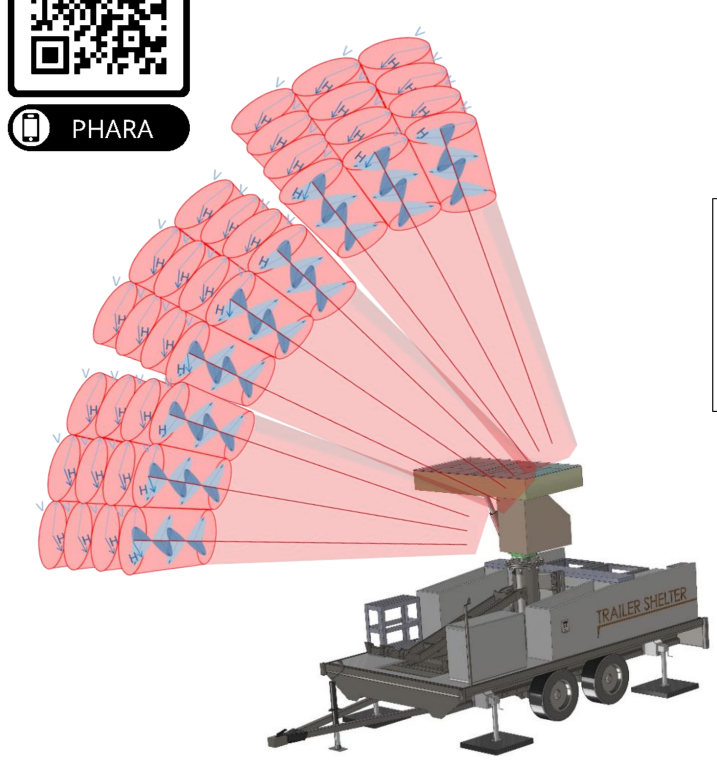
σ_n^2: Noise variance

MLE

$$\log\left(p(\hat{\mathbf{Z}}^{\mathrm{PSD}}|\theta)\right) = -\left[\sum_{l=1}^{L}\sum_{n=1}^{N}\log\left(\pi\left(\mathbf{F}_{l,n}(\theta)\right)+\sigma_n^2\right)+\frac{\hat{\mathbf{Z}}_{l,n}^{\mathrm{PSD}}}{\mathbf{F}_{l,n}(\theta)+\sigma_n^2}\right]$$

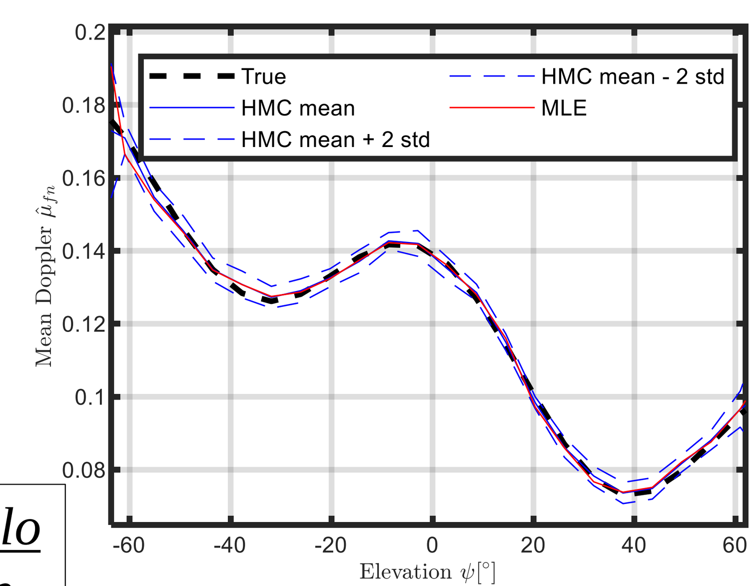
$$\{\hat{\theta}\}_{\{k=1\}}^{K(\mathrm{MLE})} = \arg\max_\theta \log\left(p(\hat{\mathbf{Z}}^{\mathrm{PSD}}|\theta)\right)$$

PHARA



$\hat{\mathbf{Z}}^{\mathrm{PSD}}$: Doppler Power Spectral Density (PSD) measurements :[Elevation x Doppler velocity]

F: Expected Doppler Power Spectral Density (PSD) model :[Elevation x Doppler velocity]



HMC

Hamiltonian: $H(\theta, p_\theta) = U(\theta) + K(p_\theta)$,
Potential Energy: $U(\theta) = -\log\left(p(\hat{\mathbf{Z}}^{\mathrm{PSD}}|\theta)\right)$,
Kinetic Energy: $K(p_\theta) = \frac{1}{2}\mathbf{p}_\theta^{\mathrm{T}}\mathbf{M}_\theta^{-1}\mathbf{p}_\theta$

The iterative <u>Markov Chain Monte Carlo (MCMC)</u> approach: till the Hamiltonian is converged

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