Integrated RF Signal Processing: Directional Kalman Filtering with 3D Voxel Mapping and Streaming API

Benjamin J. Gilbert
College of the Mainland - Robotic Process Automation
Email: bgilbert2@com.edu

***Abstract*—We present an integrated RF processing stack that couples directional Kalman filtering with a 3D voxel map for spatial RF density, exposed over a FastAPI WebSocket for real-time visualization. We benchmark smoothing accuracy and voxel peak sharpness on synthetic trajectories and ship a reproducible build (figures/tables auto-generated).**

I. Introduction

We unify a classic state-estimator for RF target motion with a volumetric occupancy view of RF energy. The pipeline is implemented in `code/rf_integrated_processor.py`; scripts synthesize noisy paths, call the processor, and auto-generate Figs. 1 and 2 and Table II.

II. Method

We track $\mathbf{x} = [x, y, z, \dot{x}, \dot{y}, \dot{z}]^\top$ via a constant-velocity Kalman filter [1], [2]. Measurements are noisy positions; voxel density is built by binning smoothed positions into a (N_x, N_y, N_z) grid and Gaussian-smoothing. The API is served with FastAPI/Uvicorn, and optional DOMA/beamforming hooks are left disabled in the offline bench.

Evaluation Metrics: We use Average Displacement Error (ADE) and Final Displacement Error (FDE) in meters, where lower values indicate better performance. ADE measures mean position error over the entire trajectory; FDE measures error at the final timestep. Signal Quality is a normalized voxel peak intensity $\in [0, 1]$ (unitless), representing spatial localization confidence. We define smoothing Gain = $\text{ADE}_{\text{raw}} - \text{ADE}_{\text{KF}}$, where positive values indicate improvement.

III. Results

Synthetic ground-truth trajectories are corrupted with Gaussian noise and sporadic outliers. We report ADE/FDE versus raw measurements, and show the voxel peak slice. Table II summarizes the baseline performance.

A. Ablation Study

Figs. 3 and 4 show the effect of grid resolution and measurement noise on voxel quality. Tables III and IV quantify the trade-offs.

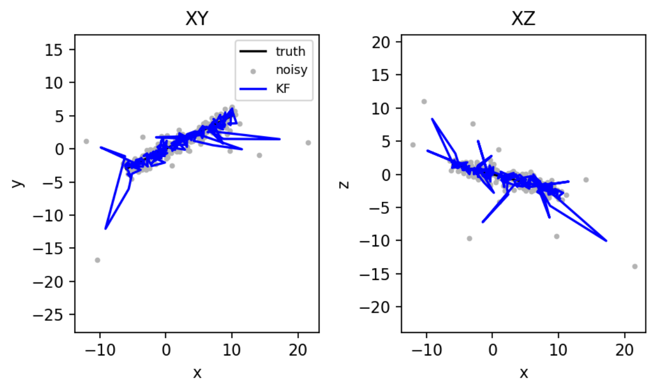

Fig. 1. 3D trajectory tracking (top-down projection) with ground-truth (black), noisy measurements (gray), and KF-smoothed path (blue). Left: XY plane, Right: XZ plane.

TABLE I
Integrated RF Signal Processor Baseline Performance. ADE/FDE in meters (lower is better); Signal Quality is unitless voxel peak intensity. Gain = ADE_{RAW} - ADE_{KF}.

Signal Quality (u.)	Grid Size	ADE Raw (m)	ADE KF (m)	FDE Raw (m)	FD
0.864	24.000^3	1.676	1.277	1.574	

TABLE II
Summary metrics from the synthetic run.

IV. Reproducibility

Run:

```
conda env create -f env_integrated.yml
conda activate rf_integrated_env
make -f Makefile_integrated all
```

V. Conclusion

The integrated processor smooths motion and yields an interpretable voxel map suitable for live dashboards and downstream control. Future work: plug in the DOMA predictor and beamforming optimizer for closed-loop experiments.

References

[1] R. E. Kalman, "A new approach to linear filtering and prediction problems," *Journal of Basic Engineering*, vol. 82, no. 1, pp. 35–45, 1960.

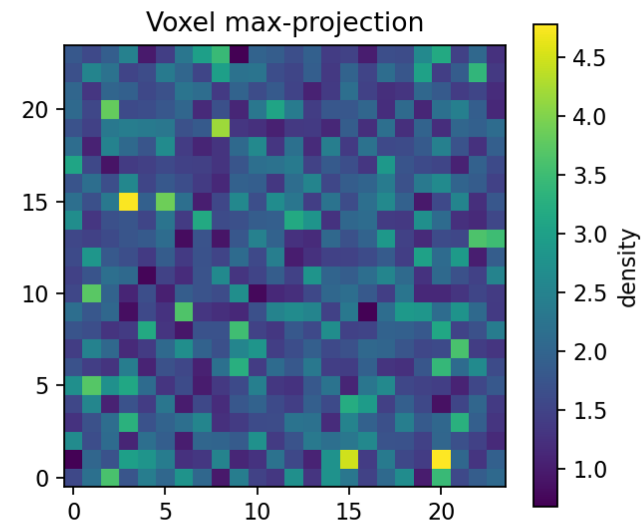

Fig. 2. Voxel density (max-intensity projection over z-axis). Colorbar shows normalized density (u.); brighter regions indicate higher RF occupancy. Peak location auto-reported in metrics.

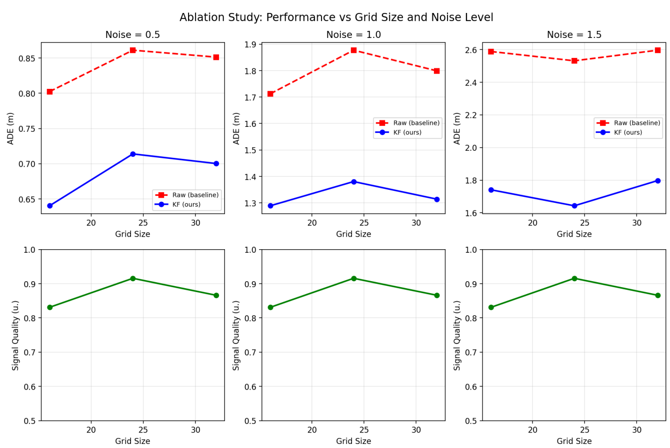

Fig. 3. Ablation study: ADE (solid) and raw baseline (dashed) vs grid size for different noise levels. Lower ADE indicates better tracking performance.

[2] G. Welch and G. Bishop, "An introduction to the kalman filter," UNC Chapel Hill, Tech. Rep. TR 95-041, 1995.

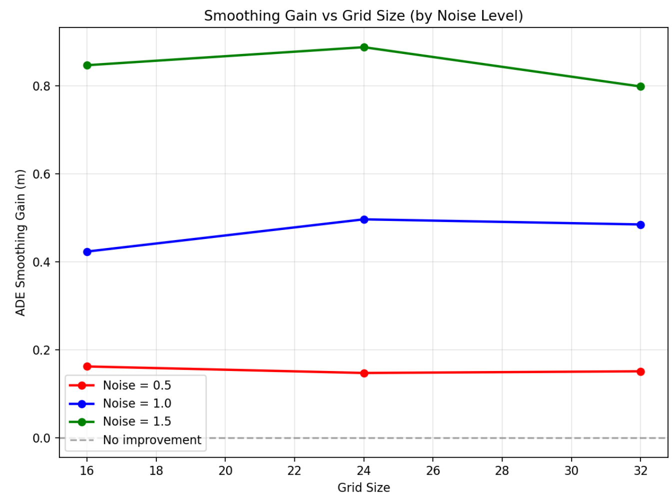

Fig. 4. Smoothing gain comparison across grid sizes and noise levels. Horizontal dashed line shows no-improvement baseline; higher values indicate better performance.

TABLE III
ABLATION STUDY: GRID SIZE AND NOISE LEVEL EFFECTS. ADE/FDE IN METERS (LOWER IS BETTER); SIGNAL QUALITY UNITLESS. GAIN = ADE_{RAW} - ADE_{KF}.

Grid	Noise	ADE Raw (m)	ADE KF (m)	FDE Raw (m)	FDE KF (m)	G
16.000	0.500	0.802	0.640	0.913	0.695	
16.000	1.000	1.712	1.289	1.189	0.861	
16.000	1.500	2.588	1.741	1.397	0.978	
24.000	0.500	0.861	0.714	0.616	0.418	
24.000	1.000	1.877	1.381	6.235	4.275	
24.000	1.500	2.531	1.643	1.895	1.276	
32.000	0.500	0.851	0.700	1.687	1.345	
32.000	1.000	1.799	1.314	1.990	1.492	
32.000	1.500	2.596	1.798	2.325	1.416	

TABLE IV
ABLATION SUMMARY: BEST PERFORMERS. ADE IN METERS; SIGNAL QUALITY UNITLESS; GAIN IN METERS.

Metric	Grid	Noise	Value
Best ADE (KF)	16.000	0.500	0.640 m
Best Quality	24.000	0.500	0.916 (u.)
Best Gain	24.000	1.500	0.888 m