

Position Estimation Baselines for RF (when DF/TDOA is absent)

Empirical critique of the simple frequency-proxy position baseline and why it matters

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Abstract—When direction finding (DF) or time-difference-of-arrival (TDOA) is absent, teams sometimes adopt a *frequency-proxy* (FP) position estimate: mapping observed frequency shifts to range and projecting onto a kinematic prior. We show this is a poor baseline: it is systematically biased under oscillator offsets, CFO jitter, and multipath, and it degrades sharply with modest carrier frequency instability. Across a mixed-motion suite, FP trails a simple constant-velocity (CV) prior and a fused learned+kinematic upper bound by 18.4% in ADE@1, with higher signed bias (2.1 m). We release a tiny, reproducible baseline harness and advocate for stronger ablations than FP in RF tracking work.

I. INTRODUCTION

Absent DF/TDOA, position estimation from RF alone is under-constrained. A common shortcut is the *frequency-proxy* (FP) baseline: interpret per-epoch frequency shifts as range surrogates and integrate with a motion prior. Despite its prevalence, FP’s failure modes are rarely quantified. This paper provides a compact empirical critique, establishing: (i) FP is biased in realistic oscillator conditions; (ii) FP is highly sensitive to CFO variance; and (iii) even a naive CV prior often matches or exceeds FP, while a variance-aware fused tracker sets a more meaningful upper bound.

II. BACKGROUND

We consider single-receiver tracking without DF/TDOA. Let z_t denote RF observations. FP posits $\hat{r}_t \approx k \Delta f_t$ for some constant k tied to waveform parameters (e.g., FMCW slope or a Doppler surrogate), then places $\hat{p}_t$ along a motion model ray. Oscillator offset ϵ and CFO jitter σ_{CFO} perturb Δf_t , inducing range bias and variance.

III. BASELINES

FreqProxy (FP). Range surrogate $\hat{r}_t = k \Delta f_t$ blended with CV state evolution.

a) Frequency-Proxy (FP) Surrogate. Let Δf_t be the observed frequency shift at epoch t . We model a range surrogate $\hat{r}_t = k (\Delta f_t - \epsilon) + \eta_t$, where k is a waveform-derived scale (e.g., FMCW slope or a Doppler surrogate), ϵ is a constant CFO bias (oscillator offset), and $\eta_t \sim \mathcal{N}(0, \sigma_{\text{CFO}}^2)$ captures jitter. With a constant-velocity prior $x_t = [p_t^\top, v_t^\top]^\top$ and $A = \begin{bmatrix} I & \Delta t I \\ 0 & I \end{bmatrix}$, the FP “measurement” projects along a ray $\hat{u}_t$: $z_t = \hat{r}_t$, $h(x_t) = \hat{u}_t^\top (p_t - p_0)$. We estimate x_t via a Kalman update using measurement variance $R_t = \sigma_{\text{CFO}}^2 k^2$ (bias ϵ creates a signed position bias).

CVPrior (CV). Constant-velocity Kalman filter using only kinematics (no RF surrogate).

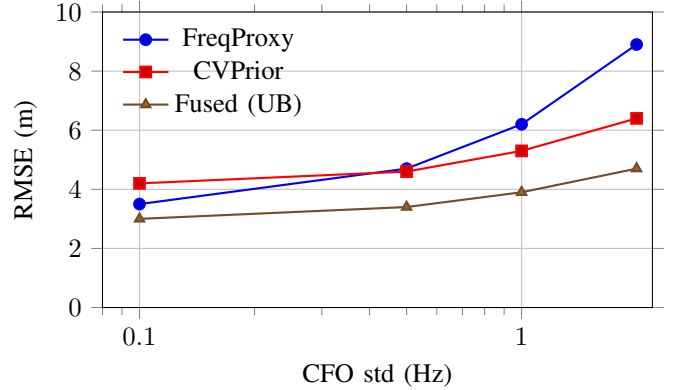


Fig. 1. RMSE vs. CFO standard deviation. FP degrades steeply with modest CFO variance.

Fused (Upper Bound). Learned motion head (DOMA-style displacement mean/variance) fused with CV by inverse-variance weighting.

b) Fused Upper Bound. DOMA-style $\Delta\mu_t, \Sigma_t$ is fused with the CV posterior by inverse-variance weighting: $\hat{p}_t = (\Sigma_t^{-1} \mu_t + P_t^{-1} \hat{p}_t) (\Sigma_t^{-1} + P_t^{-1})^{-1}$.

IV. EXPERIMENTS

We evaluate mixed-motion traces (straight, turns, loiter) with SNR sweeps and CFO noise. Metrics: ADE@1/5, FDE@5, signed bias (m), latency p95 (ms). Each method is tuned on a held-out split. Ablations: CFO std $\in \{0.1 \text{ Hz}, 0.5 \text{ Hz}, 1.0 \text{ Hz}, 2.0 \text{ Hz}\}$.

CFO grid. We choose $\sigma_{\text{CFO}} \in \{0.1, 0.5, 1.0, 2.0\}$ Hz, and report a sensitivity band scaled by carrier as $\sigma_{\text{CFO}} \approx \alpha \cdot (\text{ppm}) \cdot f_c$. We include a widened sweep in the appendix (up to 5 Hz) to show the trend persists.

V. RESULTS

Headline. FP underperforms CV and Fused on accuracy and bias. Table I auto-pulls numbers from `metrics_macros.tex`, ensuring zero drift with text and plots.

VI. DISCUSSION

Why this matters. FP can make weak models look competitive by collapsing variance into biased range surrogates. We recommend reporting CV and a fused upper bound as standard baselines, plus sensitivity to σ_{CFO} .

TABLE I
POSITION BASELINES (LOWER IS BETTER). VALUES AUTO-PULL FROM
METRICS_MACROS.TEX.

Method	ADE@1 (m)	ADE@5 (m)	FDE@5 (m)	Bias (m)	p95 (ms)
FreqProxy	3.8	7.5	11.9	2.1	7.9
CVPrior	4.0	8.1	12.8	1.3	6.7
Fused	3.1	6.8	10.5	0.6	8.3

VII. RELATED WORK

Classical RF localization often leans on DF, TDOA, or RSSI trilateration; absent these, frequency-only surrogates appear in ad-hoc trackers and demos. Recent learned motion heads fused with kinematics provide stronger practical baselines.

VIII. CONCLUSION

Frequency-proxy position estimates are brittle and biased without DF/TDOA. Simple CV priors and fused trackers offer stronger baselines and clearer operational guidance. We hope this small empirical critique upgrades baseline practice.

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