Lightweight Distance and Relative Radial Velocity Estimation with a Passive RF Receiver

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1. Motivation

- Most UAVs rely heavily on GNSS, but it can become unreliable or unavailable under obstruction, jamming, and spoofing [1], [2]
- Alternatives have limitations: inertial navigation accumulates error, vision/LiDAR depend on environmental conditions, radar and dedicated RF ranging require transmission, increasing detectability [1], [3]
- Exploiting signals of opportunity (ambient Wi-Fi, cellular, or broadcast) is ideal where low detectability matters [2]

2. Research Question

To what extent can a single passive, unsynchronized, and computationally lightweight RF receiver estimate distance and relative radial velocity?

This question is divided into the following sub-questions:

- What passive RF-based methods exist for estimating distance and relative radial velocity, and what requirements do they impose?
- Which methods are suitable for a passive receiver with limited computational complexity and signal knowledge?
- How accurate and stable are the selected methods under controlled laboratory conditions, considering effects such as multipath, antenna orientation, clock offset, and clock drift?

3. Related Work

Method	Quantity	Main limitations	Complexity
RSSI-based ranging [4], [5], [6], [7], [8, p. 102], [9], [10]	**Distance**	**Multipath / calibration-dependent**	**Low**
Time of arrival (ToA) [4], [5]	Distance	Needs tight TX–RX sync	Medium
Time difference of arrival (TDoA) [4], [5], [11]	Position	Needs synchronized infrastructure	Medium
Phase-based ranging [12], [13]	Distance	Ambiguous modulo wavelength, multipath	High
Direct Doppler [2], [14], [15], [16], [17]	**Velocity**	**Clock offset and drift needs to be compensated**	**Low**
Carrier phase tracking [18]	Velocity	Needs uninterrupted phase continuity	High

4. Implementation

- Prototype built on the AMD RFSoC 4x2 development board
- Extends the RFSoC-MTS overlay [19]
- Shared preprocessing pipeline feeds both estimators
- **RSSI / distance:** average power $\hat{p}_r$ from $|x_{\mathrm{bb}}[m]|^2$, convert to dBFS, then invert the calibrated log-distance path-loss model for distance
- **Doppler / velocity:** Kay's frequency estimator [15] as the primary estimator, clock offset removed by before–after bracketing

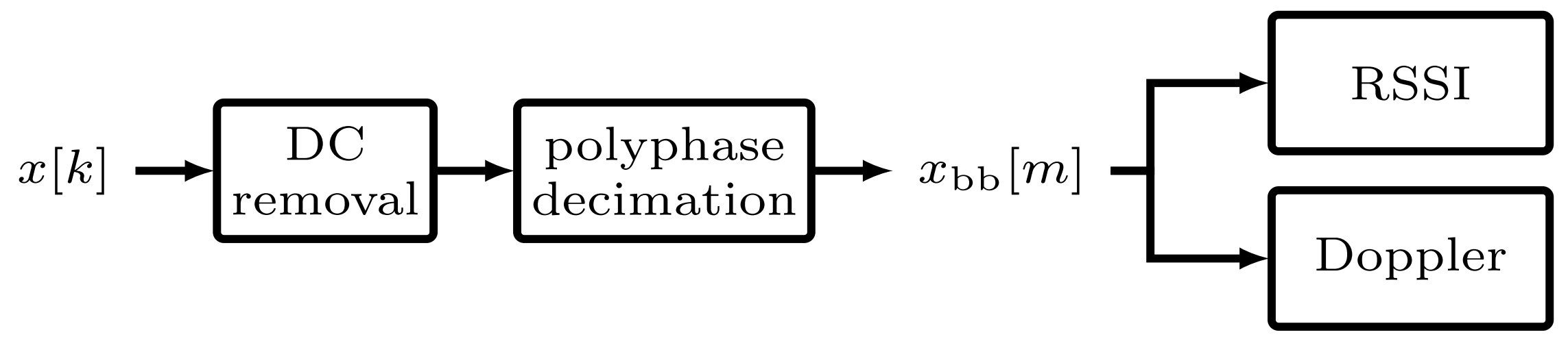


Fig. 1. Software preprocessing pipeline.

5. Evaluation

- USRP transmits a continuous-wave tone near $2.41\ \mathrm{GHz}$
- Indoor laboratory room, line-of-sight

Q1: Can calibrated RSSI give coarse distance?

- Log-distance path-loss model calibrated from 3 reference points: $\hat{n} = 1.64$, within the 1.6–1.8 range for indoor line-of-sight [8, p. 104]
- Mean absolute percentage error of 6.3% over 5 test positions
- But antenna orientation alone changes RSSI by almost $7\ \mathrm{dB}$ at a fixed distance, a distance factor of about 2.7
- *Coarse, calibration-dependent feature, not precise ranging*

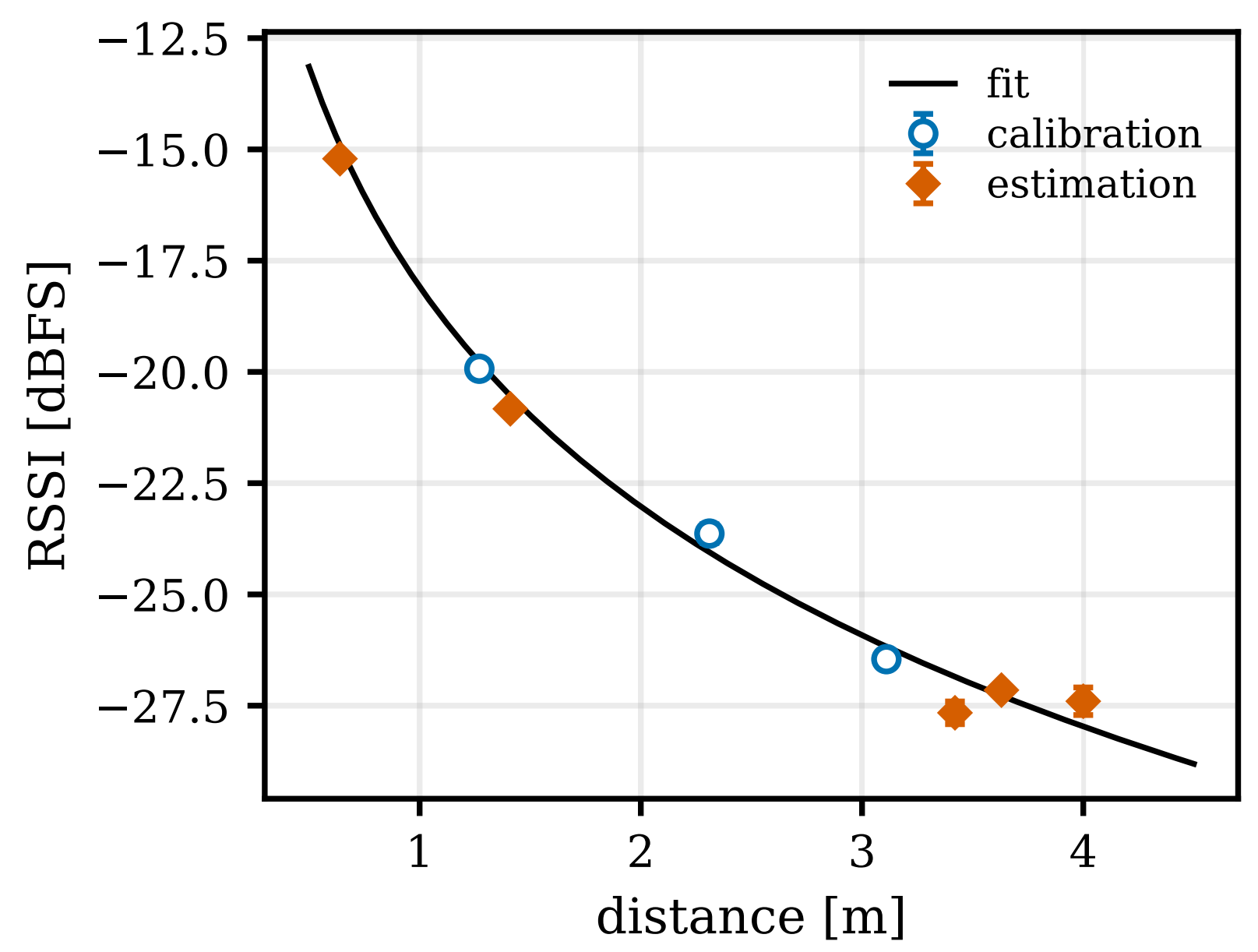


Fig. 2. Calibrated RSSI path-loss model.

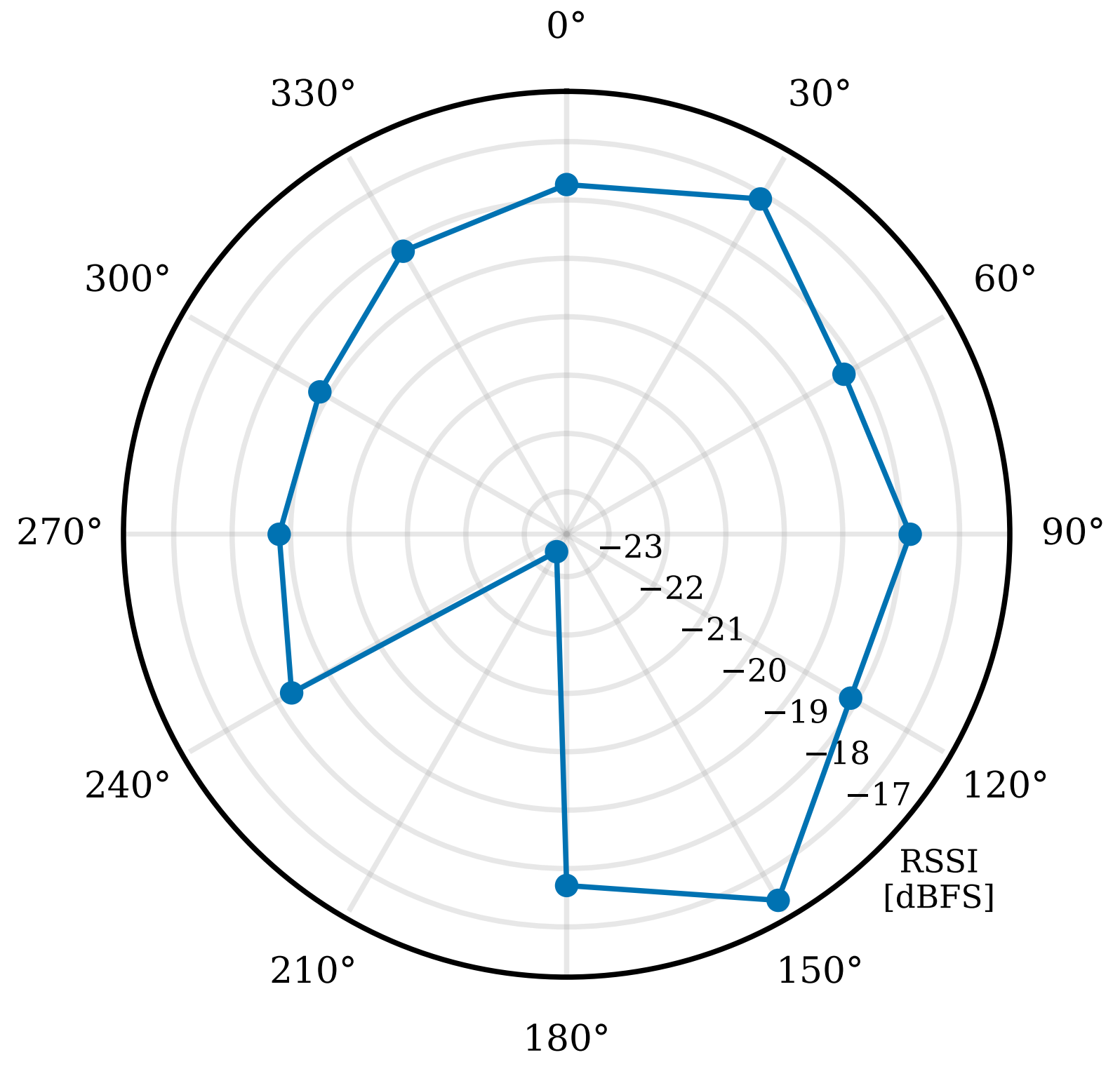
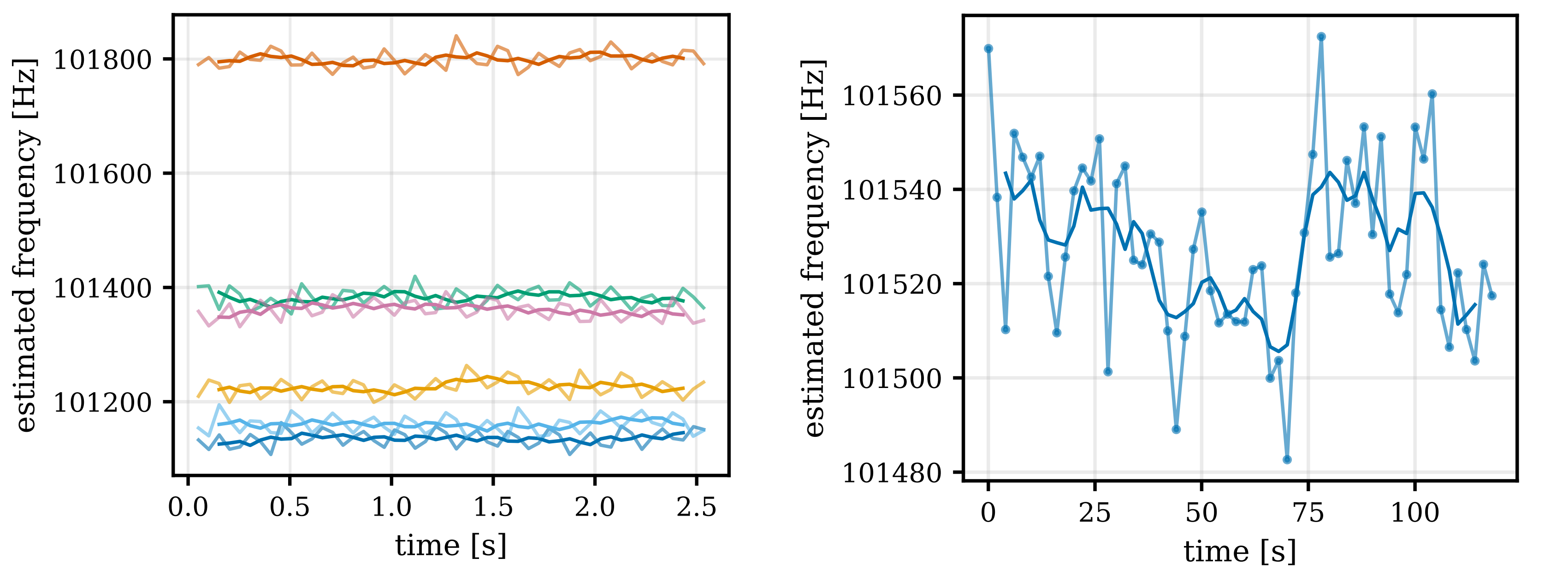


Fig. 3. Effect of receiver antenna orientation on RSSI at a fixed distance of $1\ \mathrm{m}$.

Q2: What capture length stabilizes the frequency estimate?

- Residual std drops from $\sim 64\ \mathrm{Hz}$ at $2.36\ \mathrm{ms}$ to $\sim 13\ \mathrm{Hz}$ at $4.19\ \mathrm{ms}$, then only to $\sim 10\ \mathrm{Hz}$ at $7.86\ \mathrm{ms}$, showing that oscillator instability dominates beyond $\sim 4\ \mathrm{ms}$
- 16×2^{20} samples ($4.19\ \mathrm{ms}$) selected as the operating point
- *Short-term stability supports before–after bracketing*



(a) Short-timescale measurement: six $2.5\ \mathrm{s}$ trials.

(b) Long-timescale measurement: one $2\ \mathrm{min}$ trial.

Fig. 4. Clock-drift characterization with the transmitter and receiver stationary. The bold curves show a 5-sample moving average.

Q3: How accurate is Doppler velocity with clock-offset bracketing?

- Stationary null test (10 trials): mean $+0.01\ \mathrm{m/s}$, std $0.43\ \mathrm{m/s}$
- Correct motion direction recovered in all 12 motion trials, with MAE $0.33\ \mathrm{m/s}$ and RMSE $0.43\ \mathrm{m/s}$ against video-based reference
- *Motion error comparable to stationary baseline, suggesting clock-offset compensation and estimator uncertainty dominate*

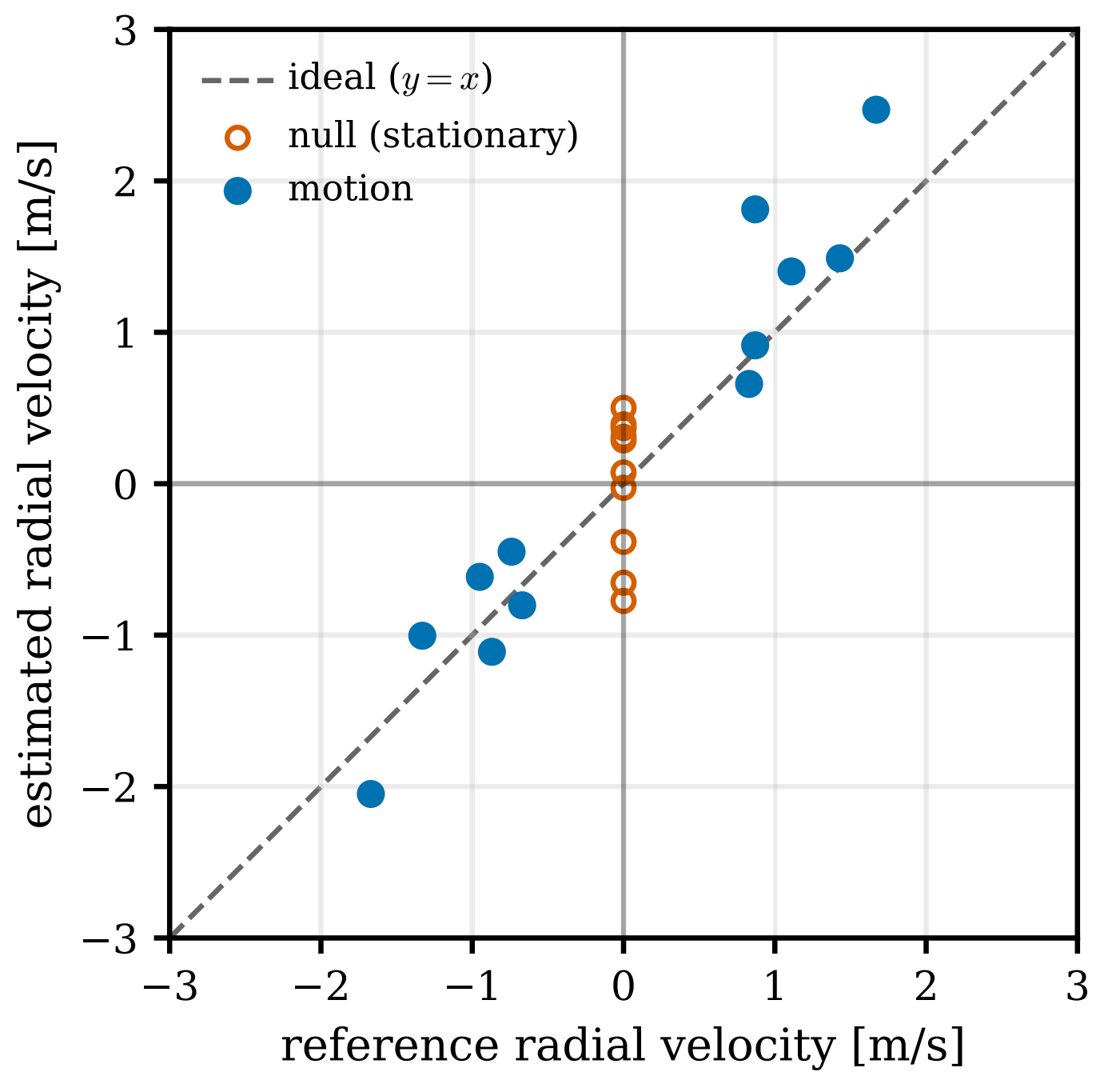


Fig. 5. Estimated radial velocity for the null test and motion trials.

6. Future Work

- Dynamic clock modeling, for example, using a Kalman filter [14]
- Motorized track or motion-capture for accurate velocity reference
- Extend to modulated OFDM signals (Wi-Fi, 4G, 5G, DVB-T)
- Move estimators to the FPGA fabric for real-time operation

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