Passive RF Self-Localization of UAVs Using Signals of Opportunity

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1 Background

- GNSS is vulnerable to **jamming and spoofing**, which can deny reliable UAV navigation.
- GNSS jamming occurs **more often than ever**, making independent backup localization increasingly relevant.[1]
- **Signals of Opportunity (SoOP)** use ambient RF sources such as cellular, Wi-Fi and broadcast signals without adding dedicated positioning infrastructure.
- The UAV remains **passive**: it only listens. This reduces detectability and helps in emission-constrained scenarios.
- SoOP signals were not designed for positioning, so they suffer from unknown timing, weak synchronization, multipath and NLOS propagation.

2 Research Question

Research question

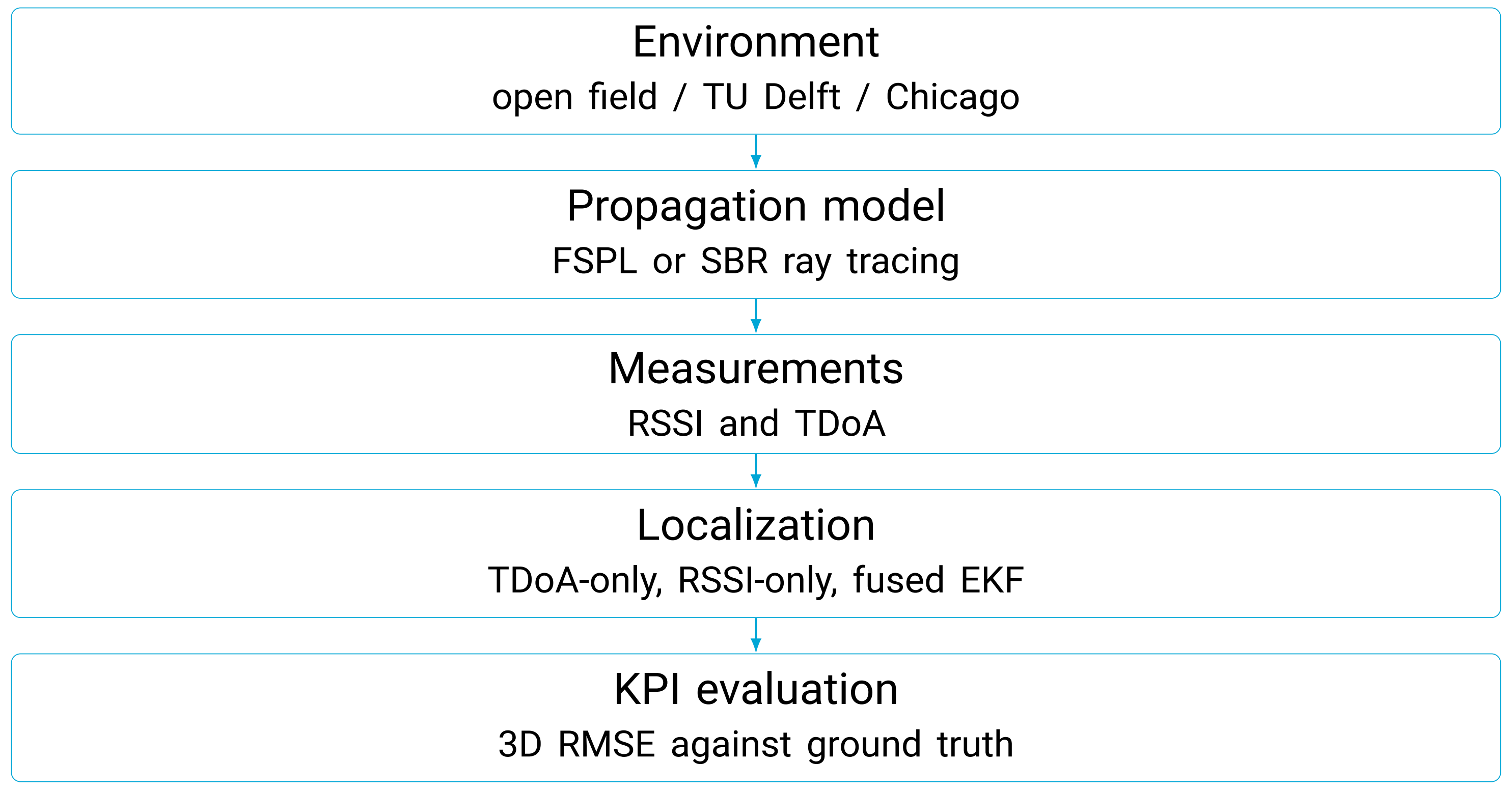
Which combinations of passive RF signal sources and measurement techniques enable reliable and accurate localization of UAVs in environments without GNSS?

a. What measurement modalities can be used for self-localization?
b. How are these measurements converted into the current UAV state/location?
c. How do different environments and transmitter geometries affect SoOP-based UAV localization performance?

3 Survey Overview

TDoA	Hyperbolic range-difference positioning based on time-of-arrival differences. High accuracy, but requires tight synchronization and is sensitive to NLOS and multipath bias.
AoA	Direction-based localization using phase or array measurements across antenna elements. Does not require time synchronization, but depends on antenna arrays and is degraded by multipath-induced angle errors.
Doppler	Velocity-induced frequency shift measurements, typically leveraging fast-moving LEO satellites. Enables positioning without timing information but depends on strong and well-characterized transmitter motion.
RSSI	Power-based distance inference using signal attenuation models. Simple and low-cost, but highly unreliable in practice due to shadowing, multipath, and environmental variability.
Hybrid	Multi-modal fusion of heterogeneous measurements (e.g., TDoA+RSSI, AoA+TDoA). Improves robustness and observability at the cost of increased system complexity.

4 Evaluation



Environment
open field / TU Delft / Chicago

Propagation model
FSPL or SBR ray tracing

Measurements
RSSI and TDoA

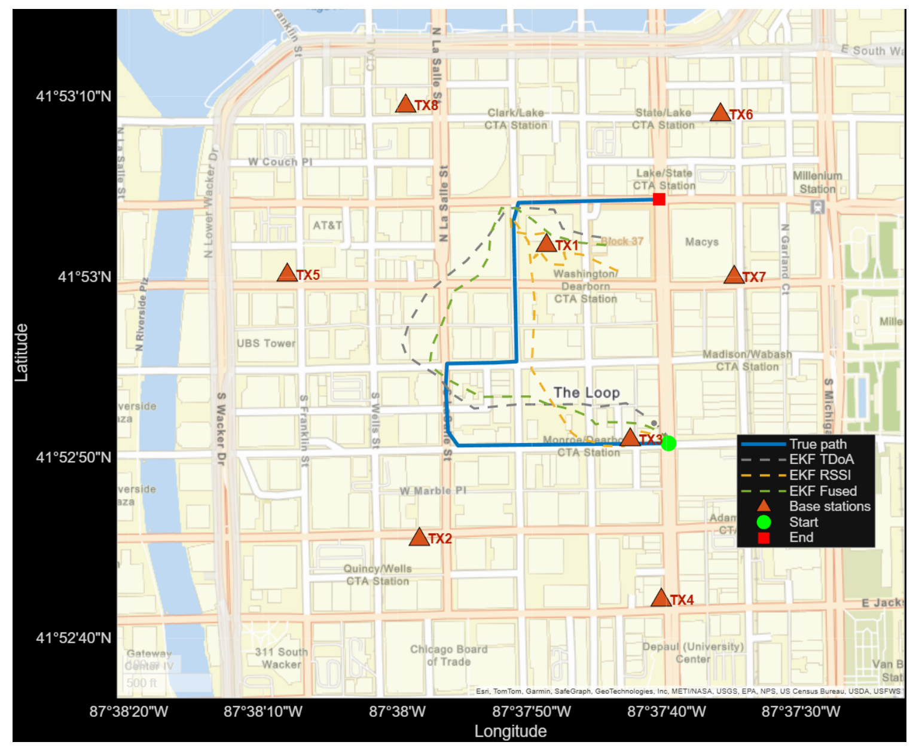
Localization
TDoA-only, RSSI-only, fused EKF

KPI evaluation
3D RMSE against ground truth

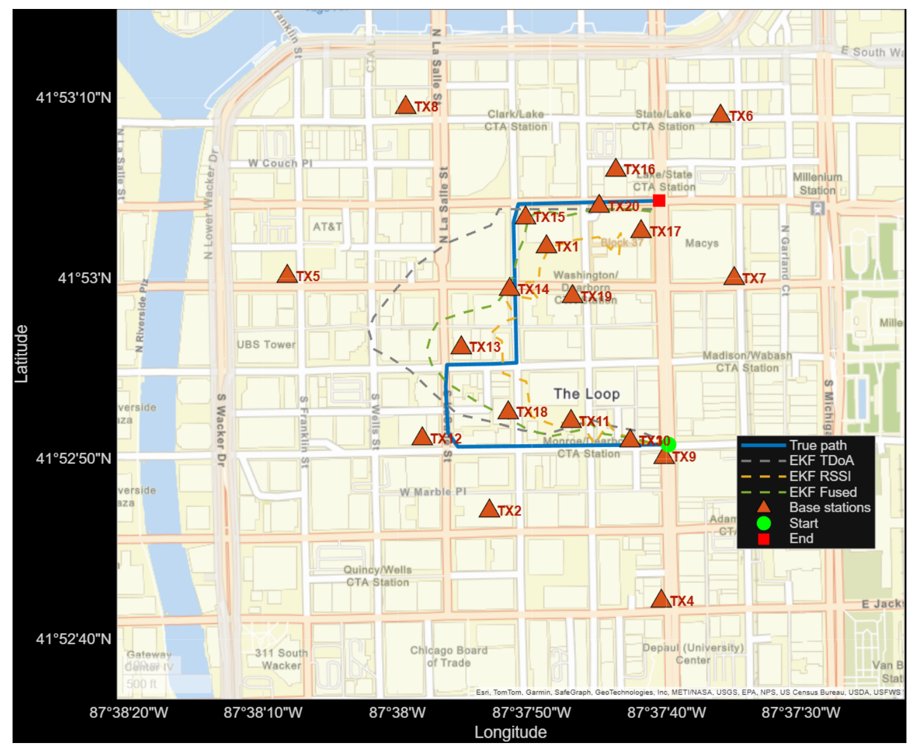
4.1 Setup

- **Open field:** 5000 m × 5000 m, free-space path loss, random transmitters, 50 Monte Carlo runs.
- **TU Delft campus:** OpenStreetMap buildings, real and handpicked transmitter layouts, SBR ray tracing.
- **Chicago city center:** dense urban geometry with LOS/NLOS transmitter configurations and an additional 20-transmitter case.
- **Estimator:** same constant-velocity EKF for all filters, isolating the measurement contribution.

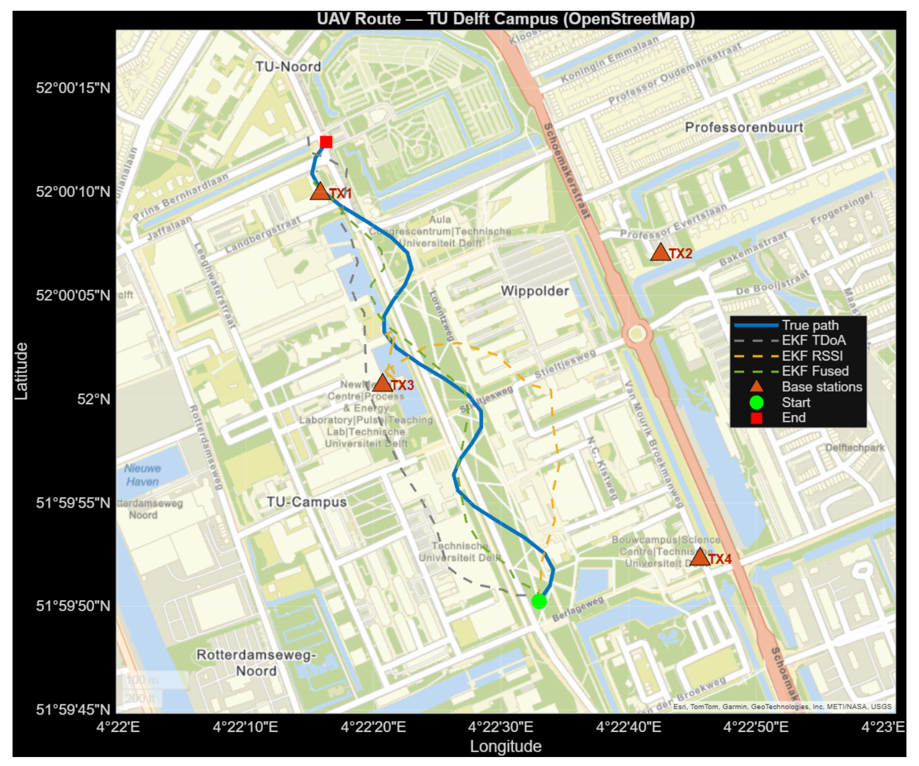
5 Route Figures



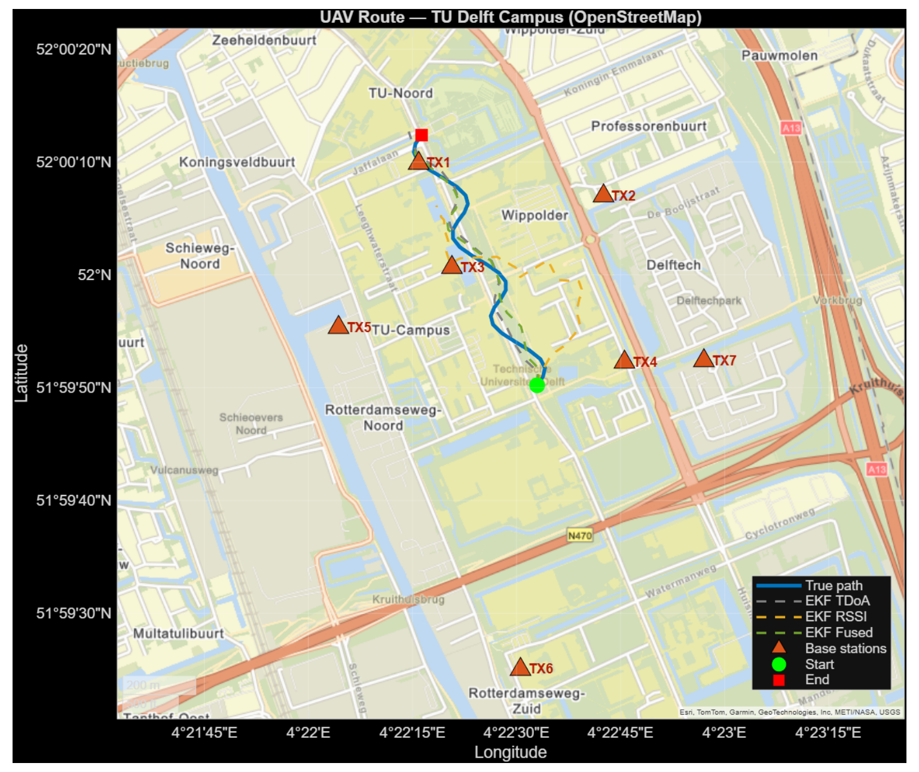
Chicago, 8 TX, TX2 at 44 m



Chicago, 20 TX, TX2 at 164 m

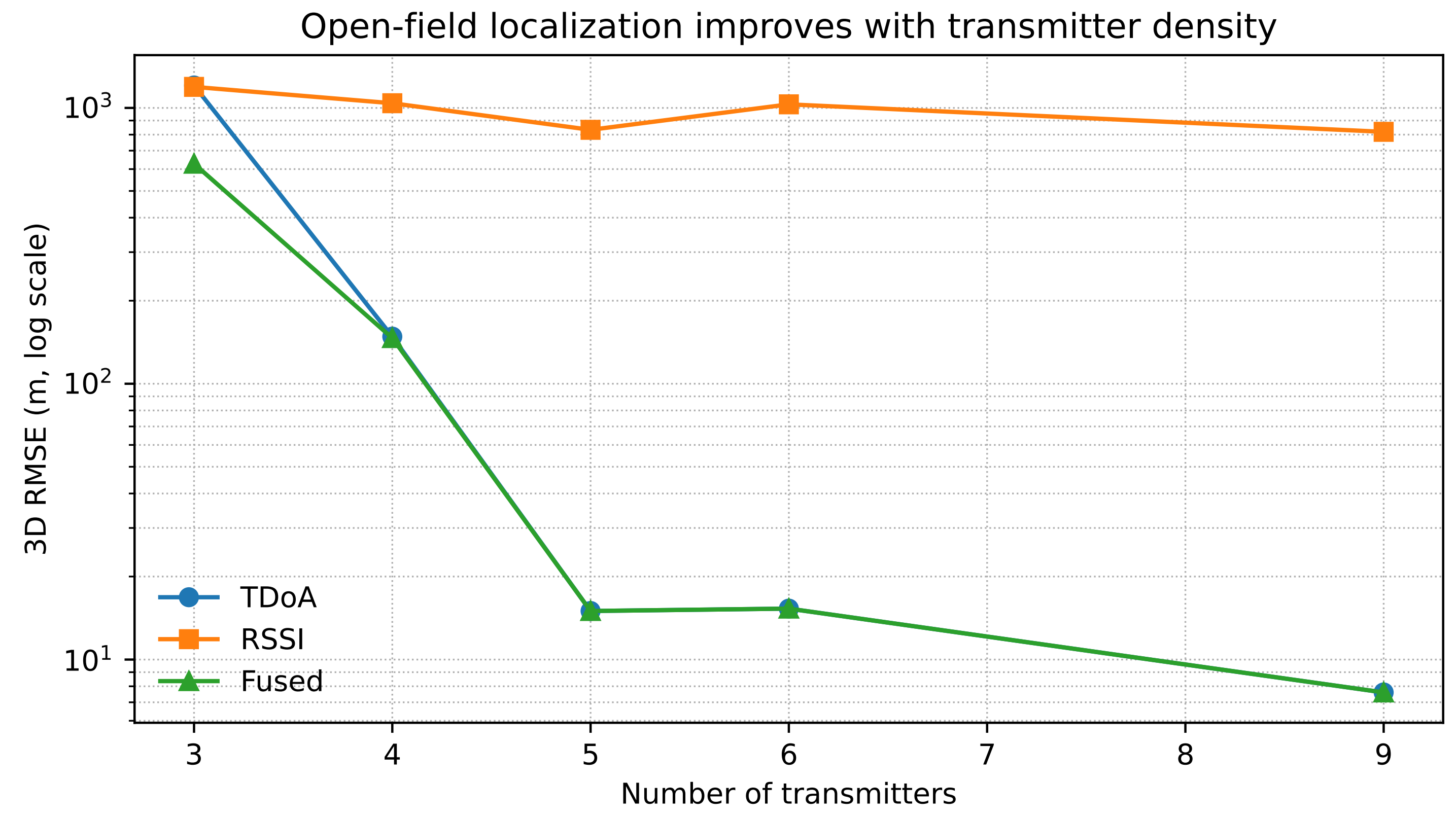


TU Delft, 4 handpicked TX



TU Delft, 7 real TX

6 Results



Configuration	TDoA	RSSI	Fused
Open field, 9 TX	7.6 m	819.0 m	7.6 m
TU Delft, 7 real TX	45.3 m	147.5 m	42.0 m
TU Delft, 4 NLOS TX	134.2 m	156.2 m	59.9 m
Chicago, TX2 at 164 m (LOS)	135.3 m	163.7 m	113.7 m
Chicago, TX2 at 44 m (NLOS)	123.1 m	172.6 m	129.5 m
Chicago, 20 TX	123.0 m	131.7 m	95.1 m

- **TDoA** is the strongest standalone modality when transmitter geometry is favorable.
- **RSSI-only** localization is consistently weakest and can become unusable in open field.
- **Fusion** helps most in challenging geometry or NLOS: TU Delft NLOS improves from 134.2 m to 59.9 m RMSE, a 55% reduction.
- **Transmitter density and geometry** dominate performance more than EKF Tuning or noise changes.

7 Conclusion and Future Work

Summarizing:

Passive RF SoOP can act as a GNSS-denied backup for UAV localization, but robustness depends strongly on transmitter and environment geometry, and measurement selection.

- Investigate adaptive measurement-noise tuning to improve estimator robustness under varying channel conditions.
- Explore Doppler-based localization techniques, motivated by the increasing availability of LEO satellite constellations.
- Improve TDoA performance in urban environments by mitigating NLOS effects and synchronization errors.
- Develop methods that relax the requirement for prior knowledge of all surrounding transmitters.

References

[1] Z. M. Kassas, J. Khalife, A. A. Abdallah, and C. Lee. "I Am Not Afraid of the GPS Jammer: Resilient Navigation Via Signals of Opportunity in GPS-Denied Environments". In: *IEEE Aerospace and Electronic Systems Magazine* 37.7 (2022), pp. 4–19. DOI: `10.1109/MAES.2022.3154110`.