mmHawkeye: Passive UAV Detection with a COTS mmWave Radar

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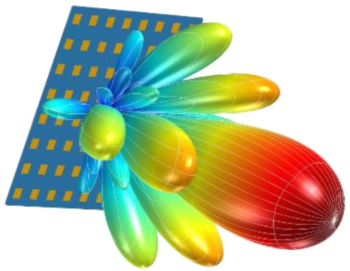

The potential threat of small UAVs

- Intrusion into personal space
- Illegal item delivery
- Public safety threat
- Human injury

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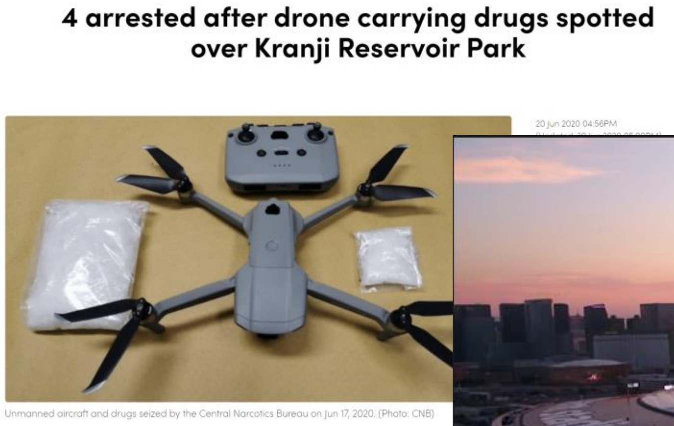

Expected performance of UAV detection system

- Passive detection
- Long-distance detection
- Low-cost and easy to deploy
- Generic for various UAVs

Potential UAV detection solution

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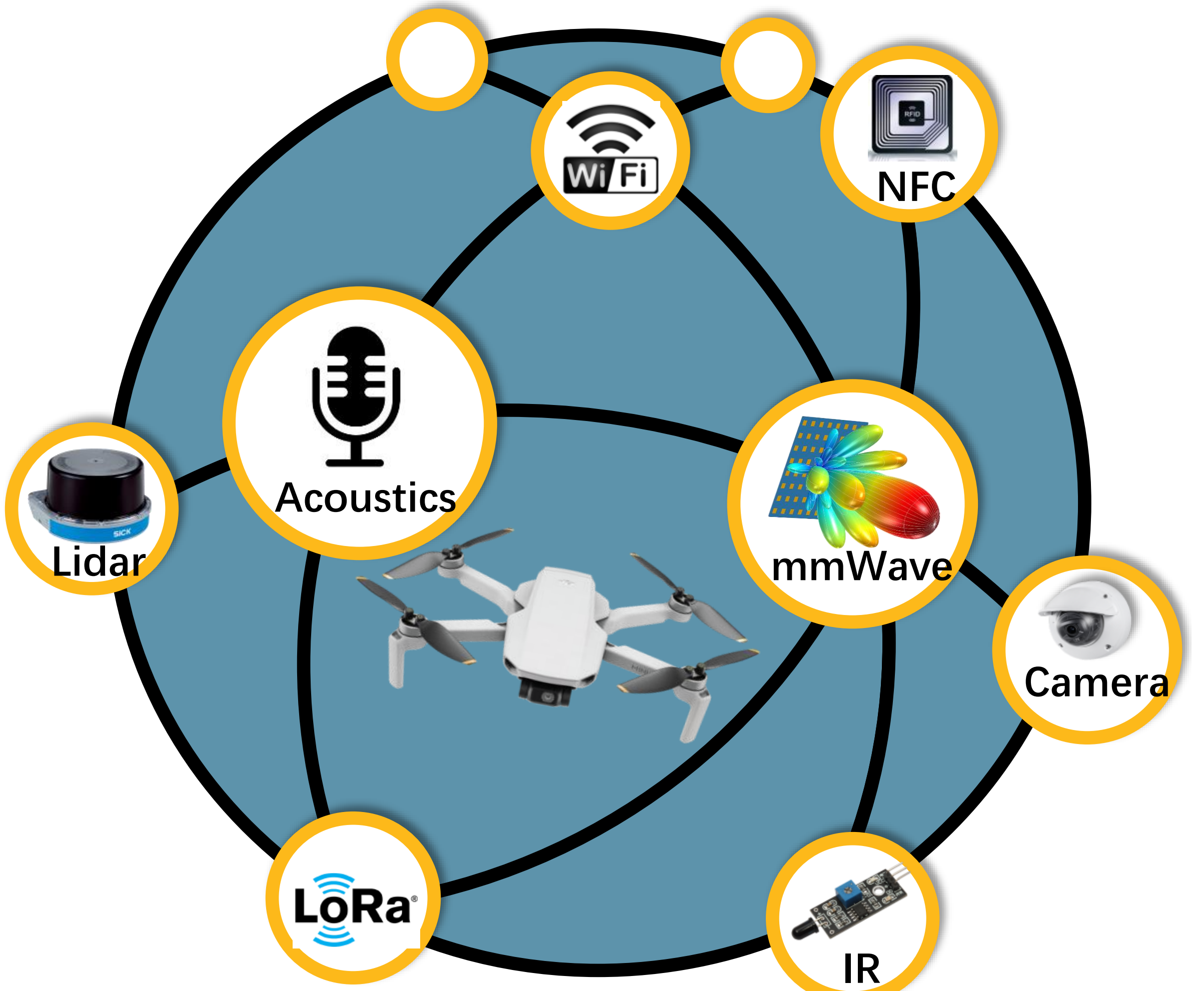
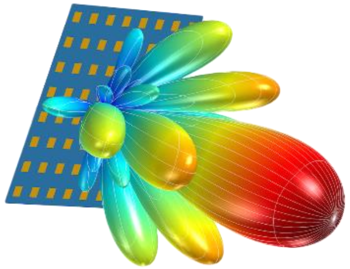
- Long-distance detection
- Low-cost and easy to deploy
- Generic for various UAVs



Advantages of the mmWave radar

- Accurate tracking capability
- Wide detection FoV
- Work in various illumination and noise conditions
- Low-cost and easy to deploy



Challenge of mmWave-based UAV detection system

- The **weak** reflected signal from the small UAV at height
- The **dynamic and unpredictable** motion of the non-cooperative UAV
- The **tightly coupled** inherent UAV features and motion-related features

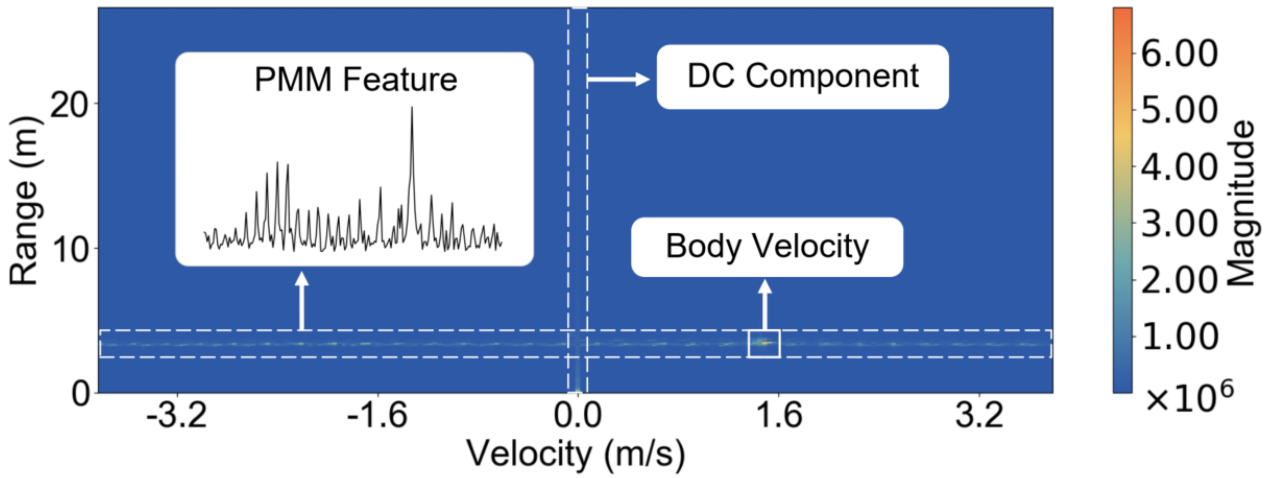
The above factors lead to the very low SNR and the uncertainty of the UAV-reflected signals

Periodic micro-motion (PMM) feature

A unique signal feature is required to extract the UAV-reflected signals

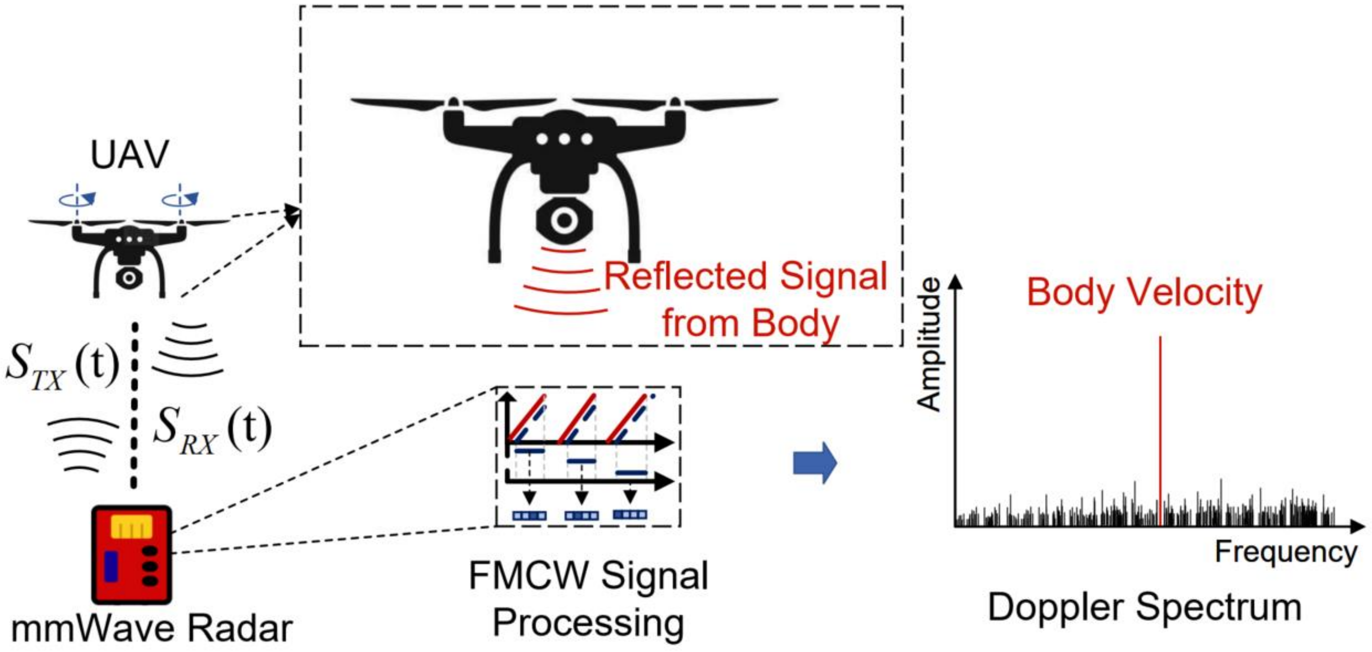
- Motion-independent
- Consistent across various UAVs
- Stable over time
- Distinguishable from noise

Periodic propeller rotation



The PMM feature of a six-wing UAV

The model of UAV-reflected signal



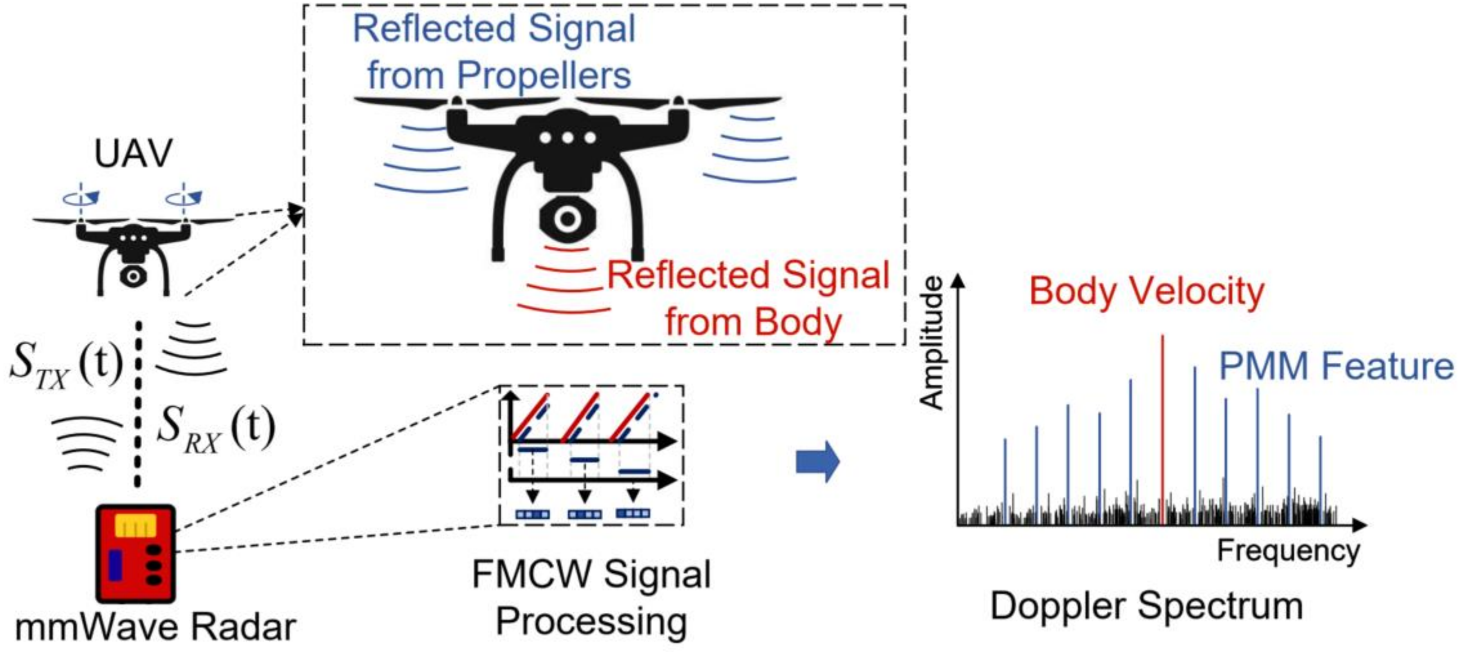
After Range-FFT:

$$S(t) = \alpha \exp[j4\pi f_c R(t)/c]$$

After Doppler-FFT:

$$S(f) = FFT\big(S(t)\big) = \alpha\delta(f - 2vf_c/c)$$

The model of UAV-reflected signal



After Range-FFT:

$$S(t) = \alpha \exp[j4\pi f_c R(t)/c]$$

$$+ \sum_{q=1}^{Q} \sum_{p=1}^{P} \beta_{pq} \exp\{j4\pi f_c [R_q(t) + \boldsymbol{R_{pq}(t)}]/c\}$$

Propeller position:

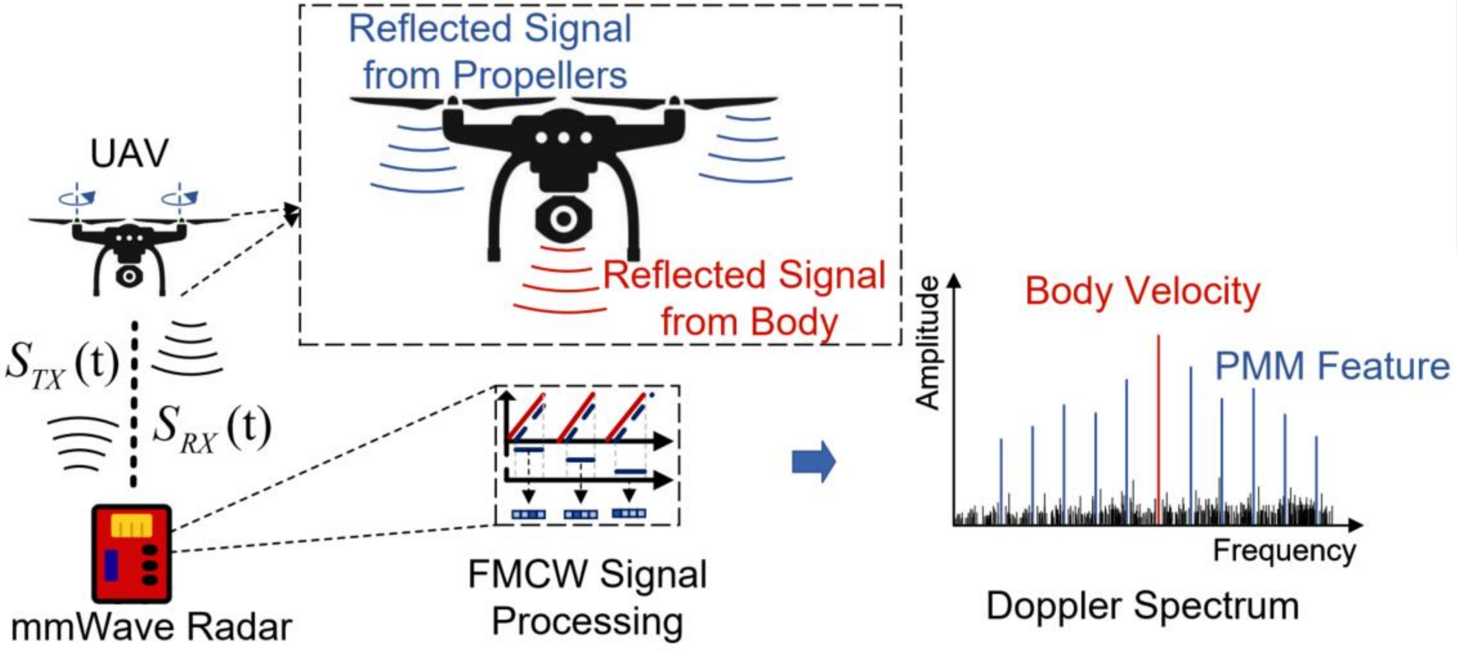
$$R_{pq}(t) \propto r_{pq} * \cos(\omega t + \varphi_{pq})$$

After Doppler-FFT:

$$S(f) = FFT\big(S(t)\big) = \alpha\delta(f - 2\boldsymbol{v} f_c/c)$$

$$+ \sum_{q=1}^{Q} \sum_{p=1}^{P} \sum_{m=-\infty}^{+\infty} \gamma_{pqm}\delta(f - 2v f_c/c - \boldsymbol{\omega m/2\pi})\}$$

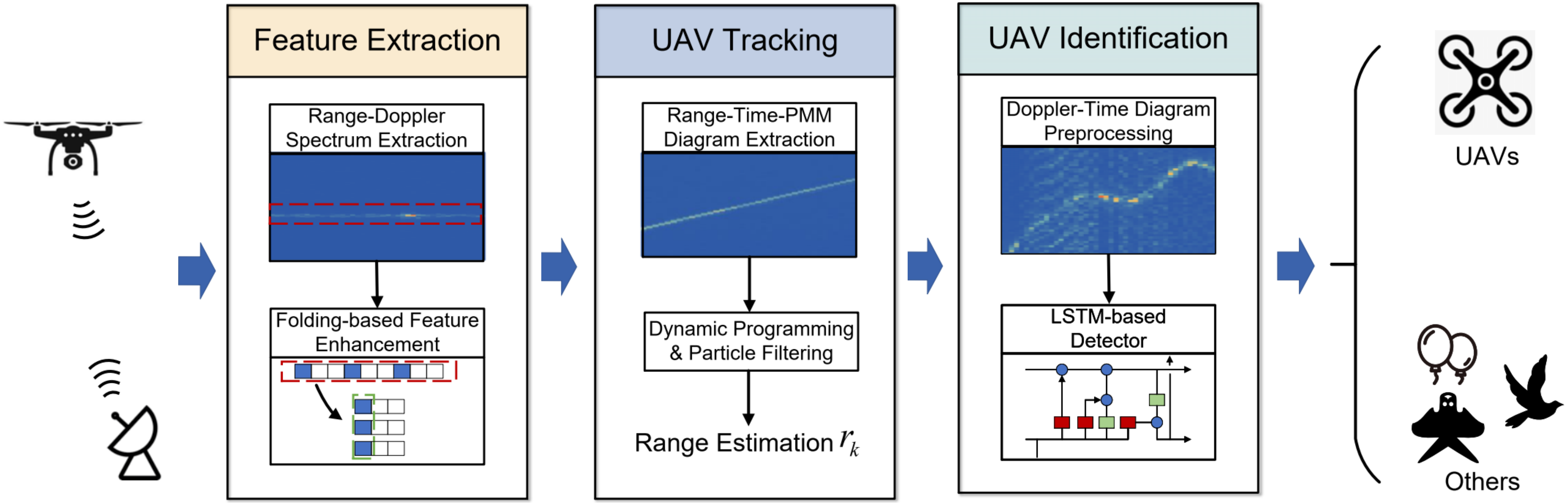
The model of UAV-reflected signal



The PMM feature:

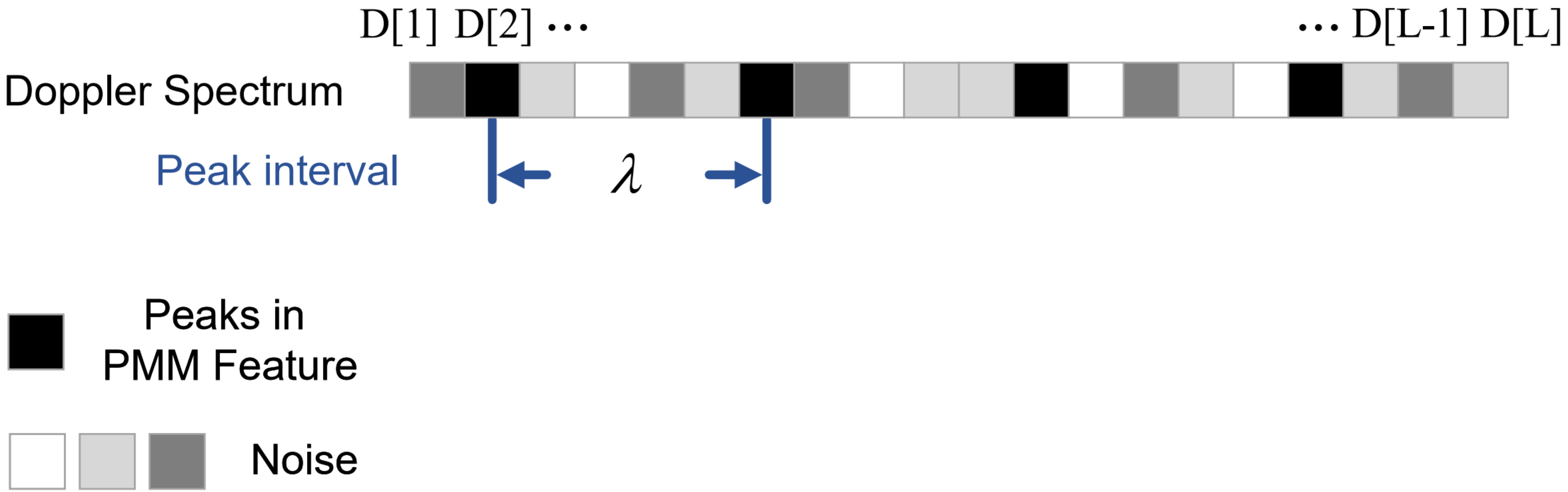
$$\begin{cases} Peak\ Pos: \ 2\boldsymbol{v}f_c/c + \omega m/2\pi & m \in Z \\ Peak\ value: \sum_{q=1}^{Q}\sum_{p=1}^{P}\gamma_{pqm} & m \in Z \end{cases}$$

mmHawkeye: Passive UAV detection with the PMM feature



Feature extraction

Challenge 1: The weak reflected signal from the small UAV at height.



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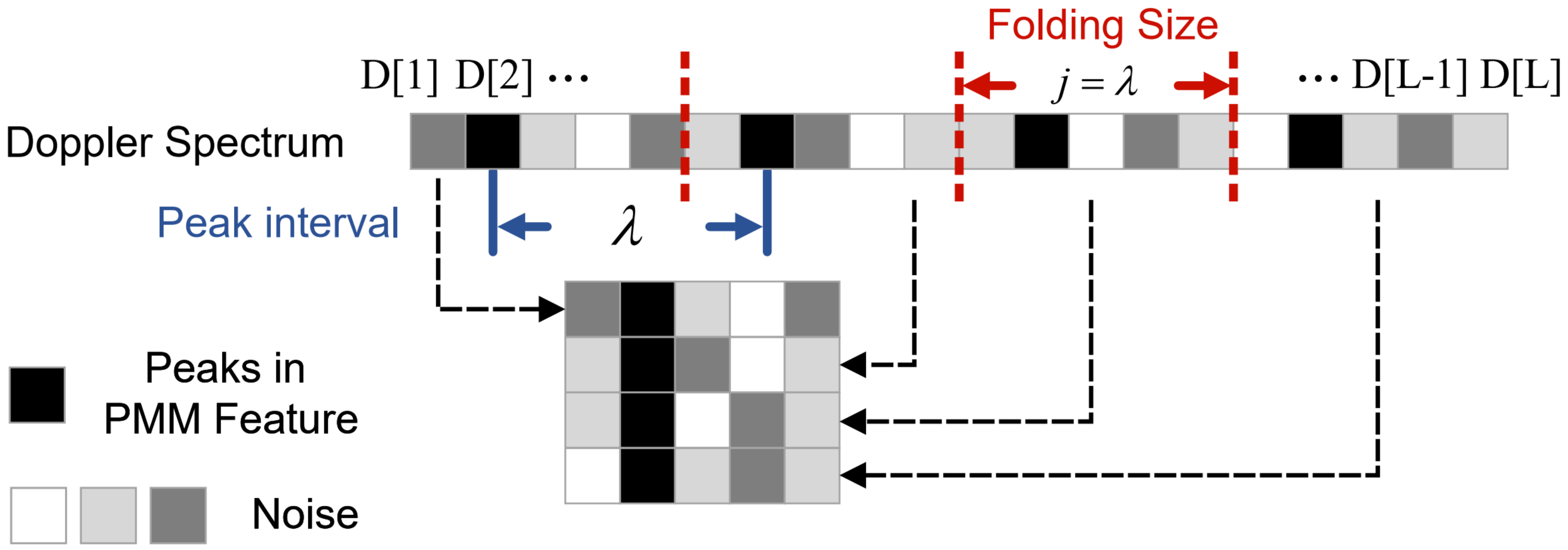

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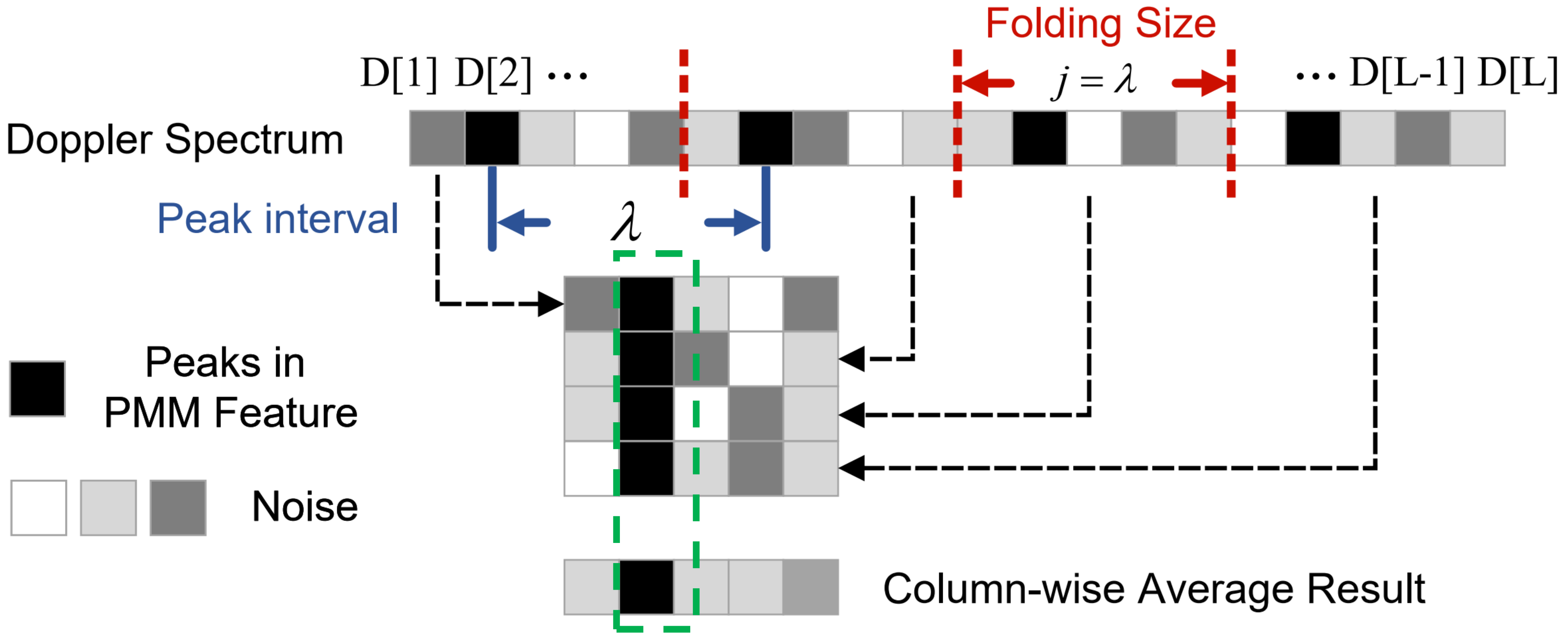
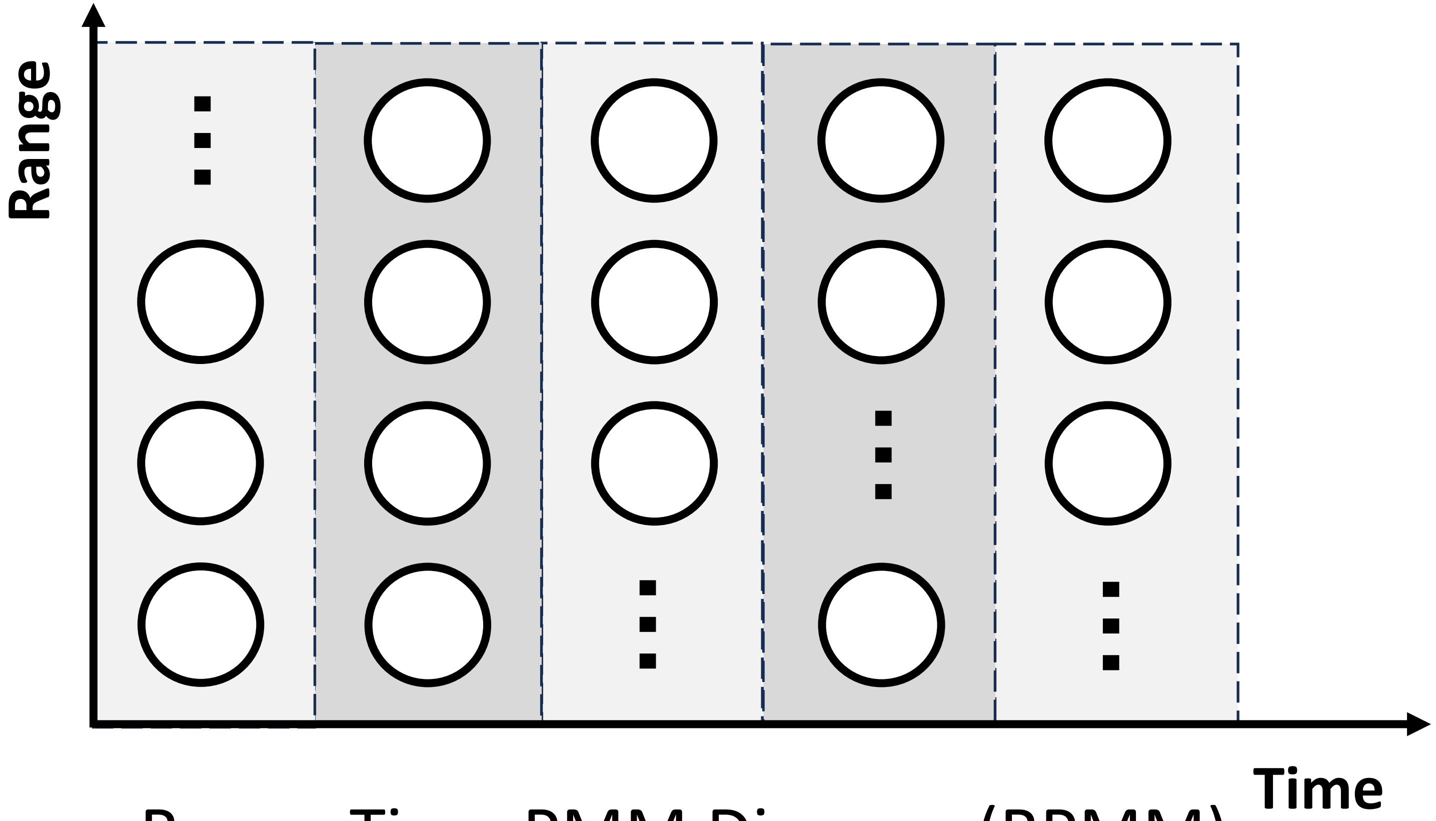


UAV tracking

Challenge 2: The dynamic and unpredictable motion of the non-cooperative UAV.



Range-Time-PMM Diagram (RPMM)

UAV tracking

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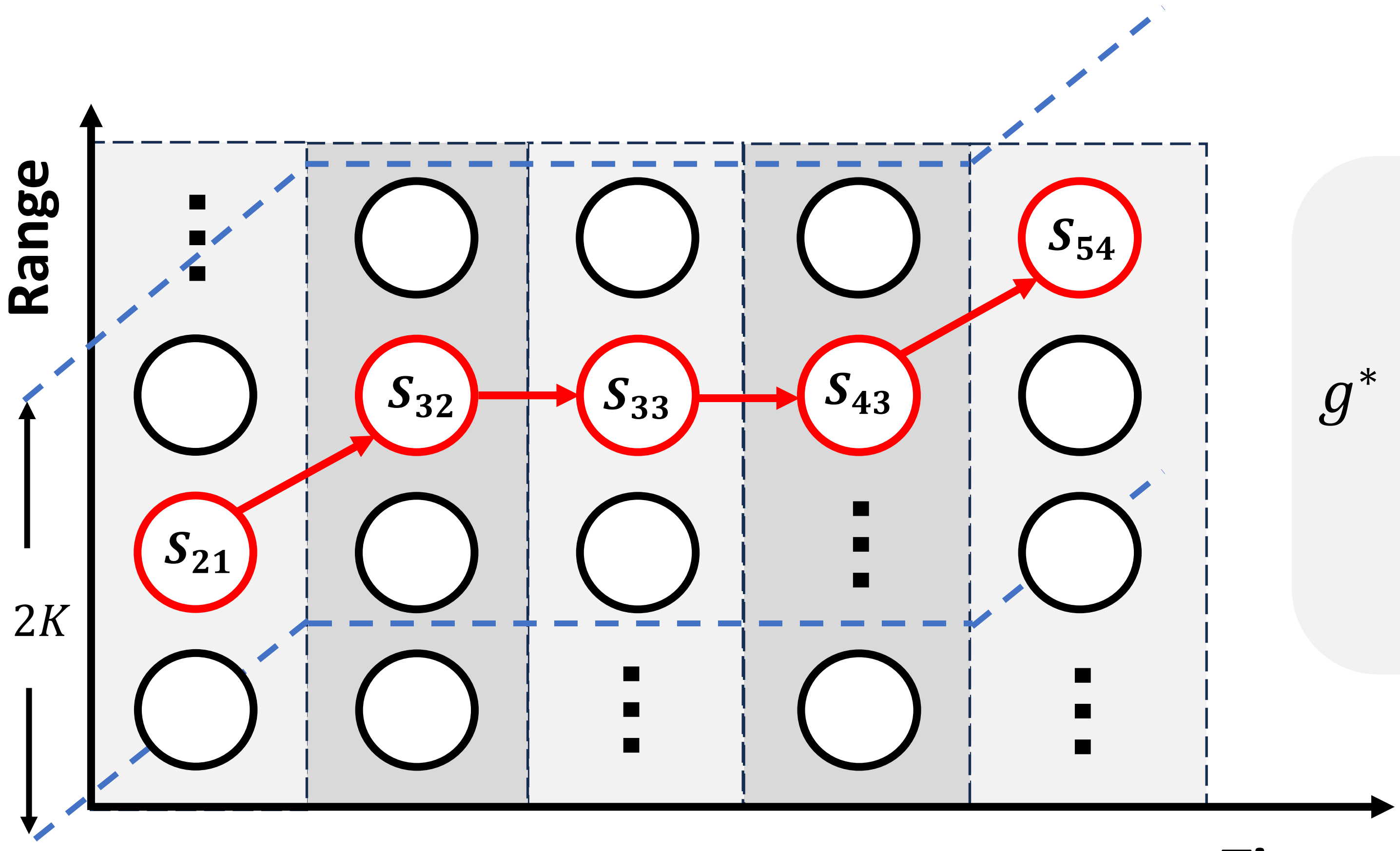


Range-Time-PMM Diagram (RPMM)

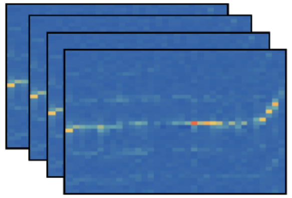
The maximum path:

$$g^* = \arg\max_g \left(\sum_{t=1}^{T} RPMM(g(t), t)\right)$$

$$s.t. \; |g(t) - g(t-1)| \leq K$$

UAV identification

Challenge 3: The tightly coupled inherent UAV features and motion-related features.



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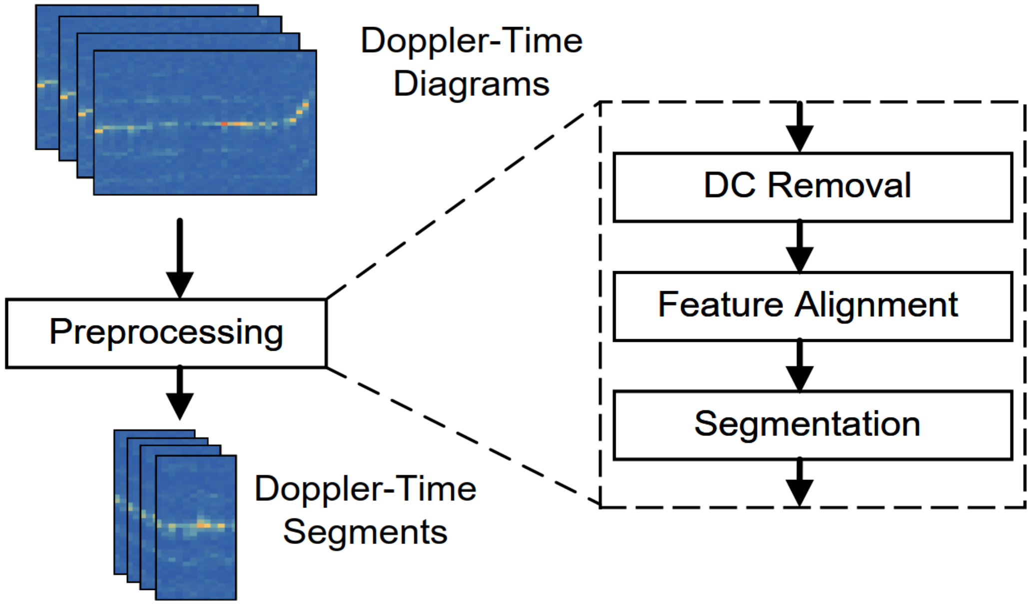

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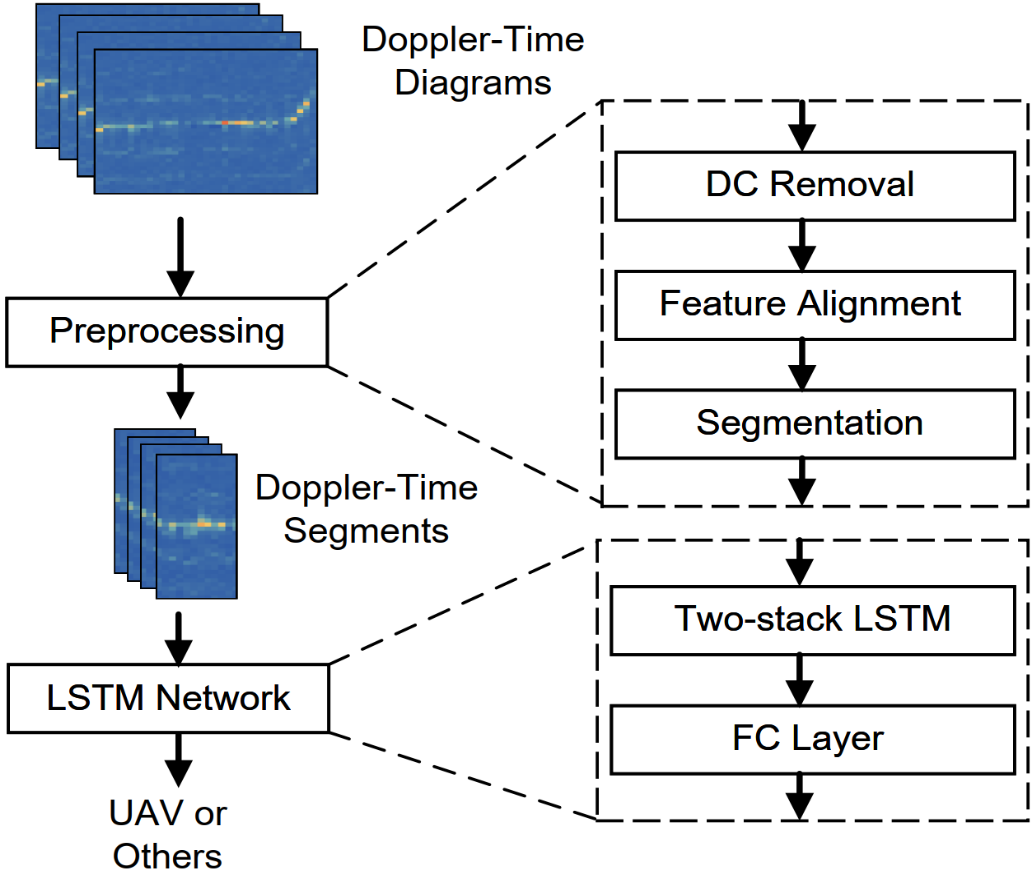
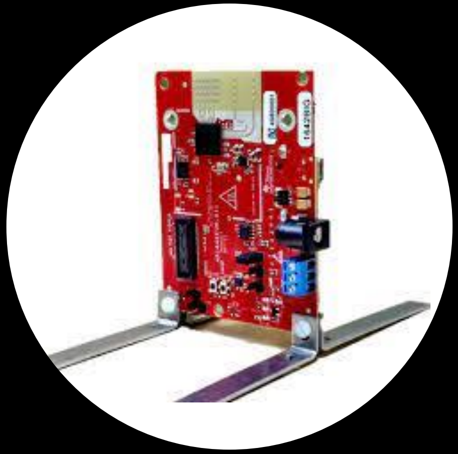


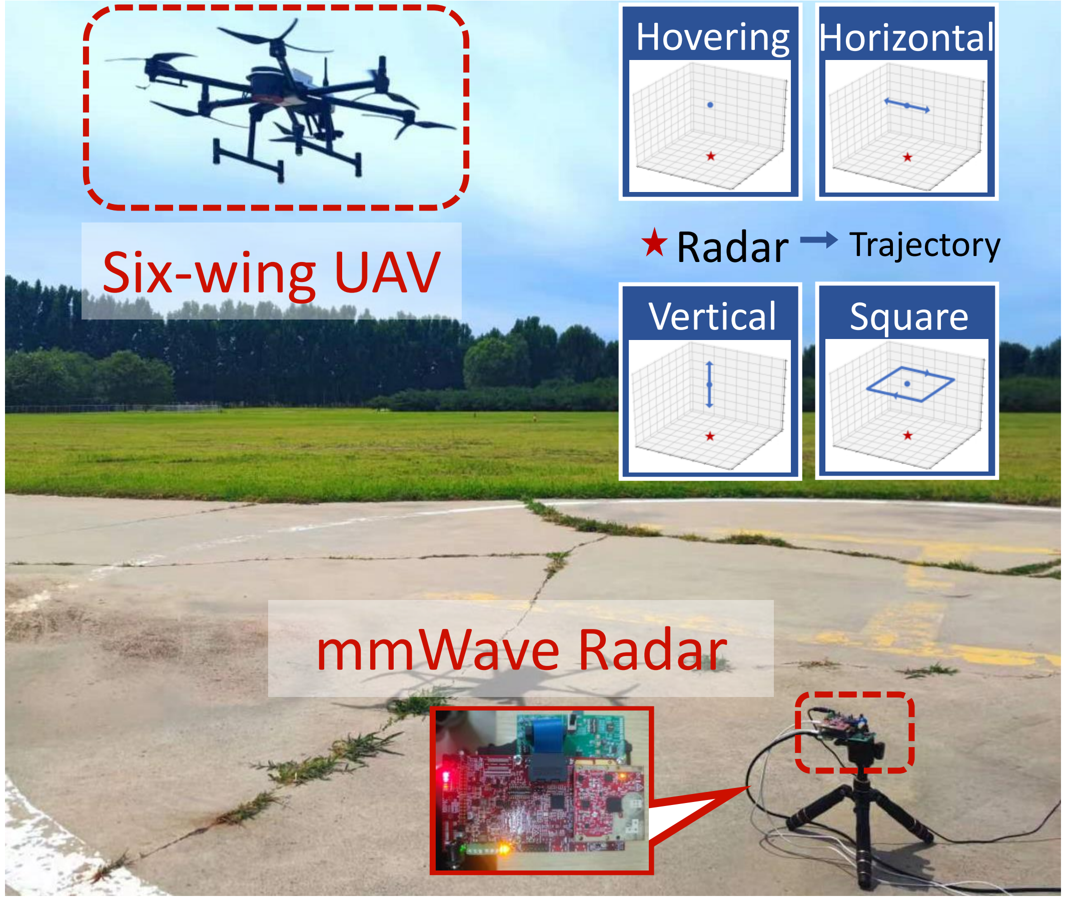
Evaluation



Implementation

The experiment scenario

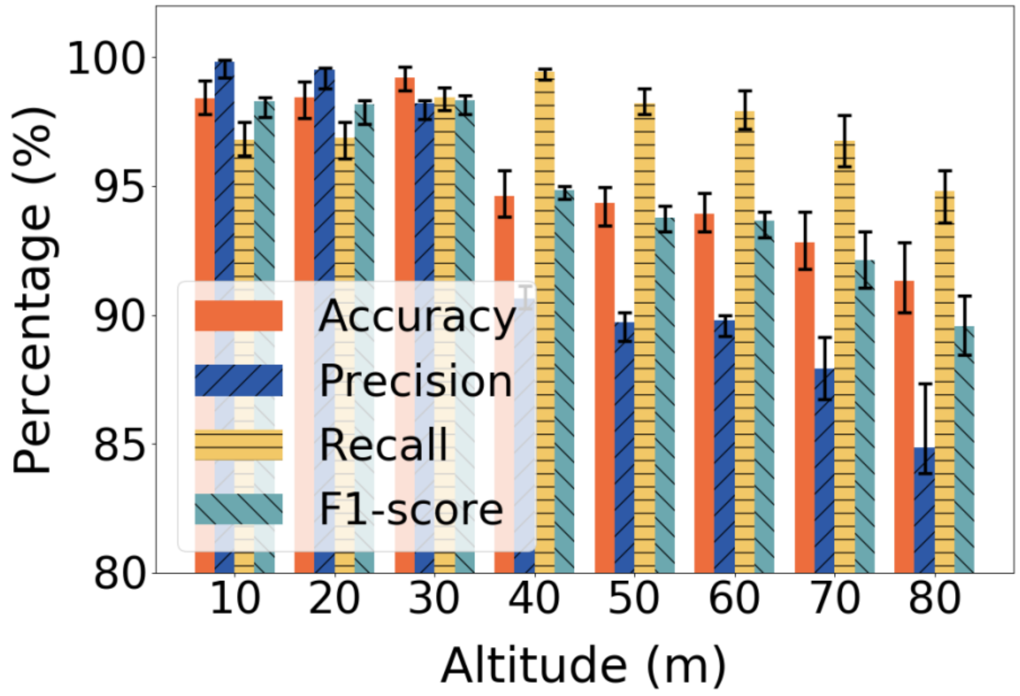
Implementation

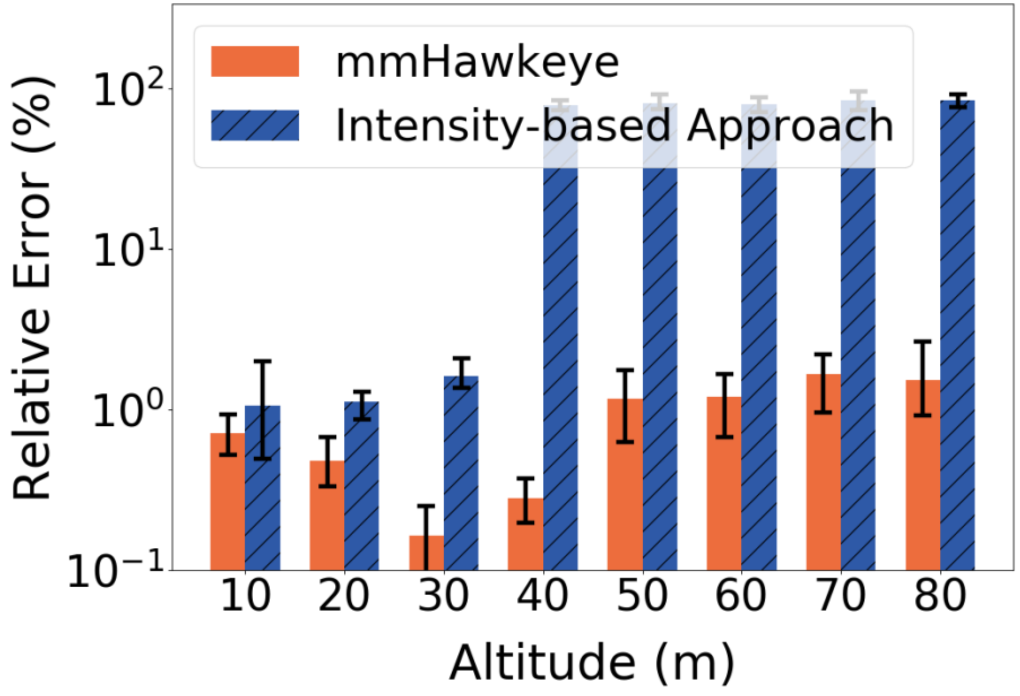


The experiment scenario

- Implementation on a COTS mmWave radar TI IWR6843ISKODS.
- A six-wing UAV with three blades per propeller is used as the detection target.
- The RTK module is used to provide the ground truth of the UAV location.
- More than 4000 seconds of signal is collected.

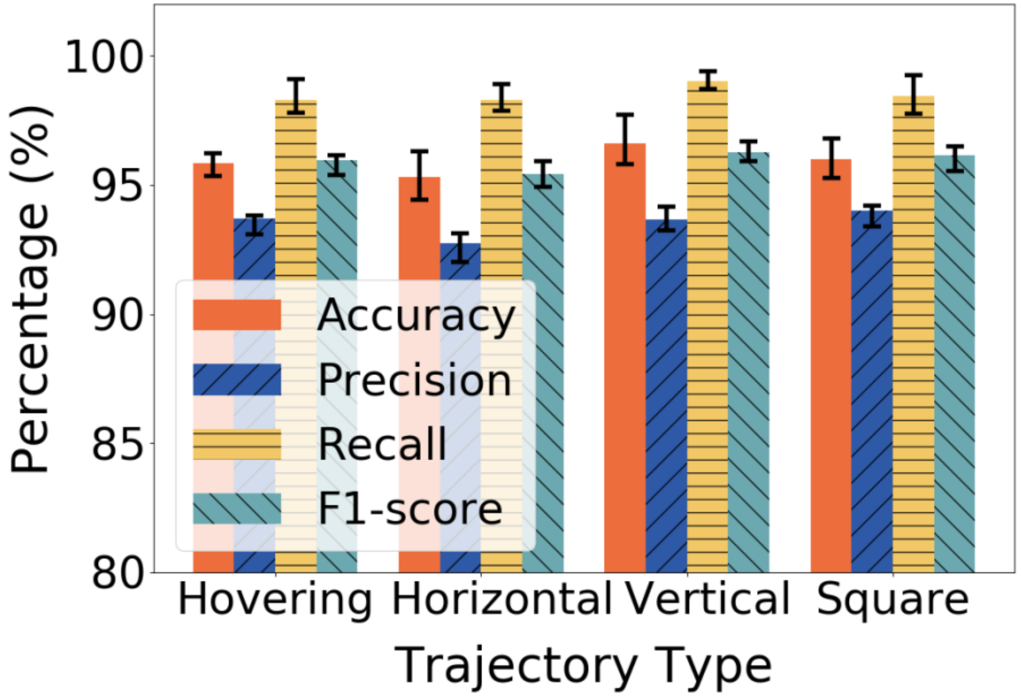
Overall performance

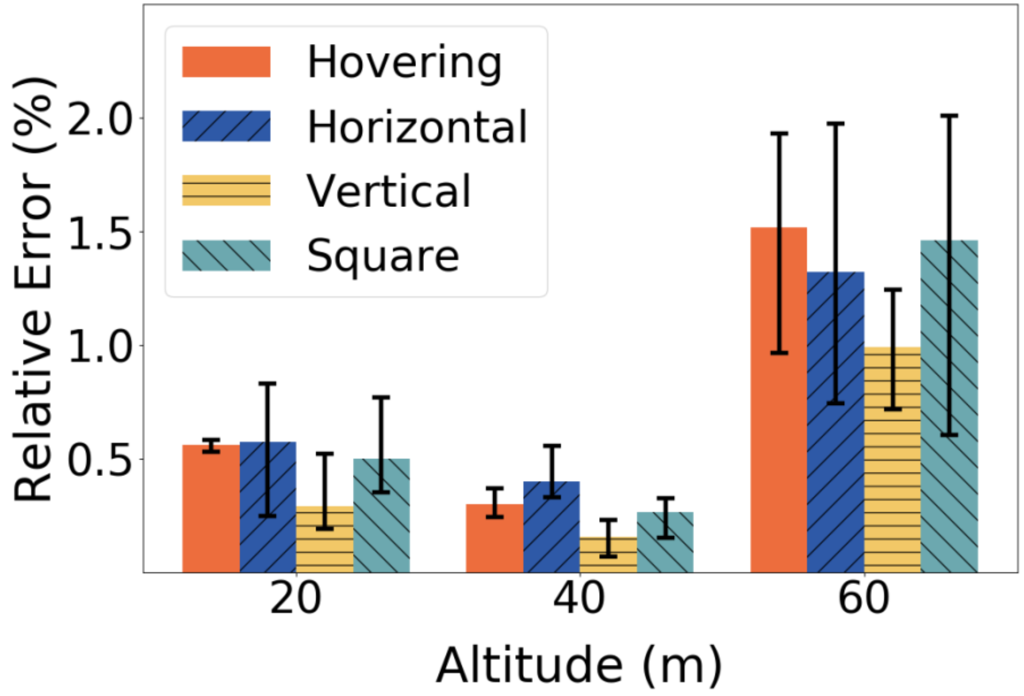




mmHawkeye achieves an UAV detection accuracy of 95.8% and a relative range error of 0.9% at a detection range up to 80m.

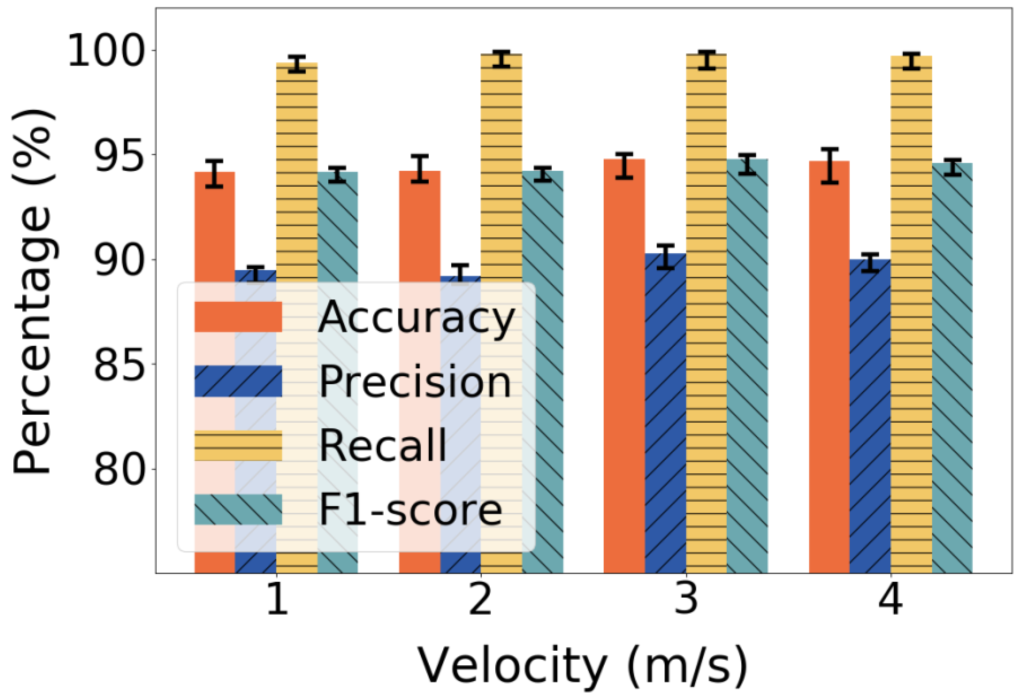
Accuracy v.s. trajectory

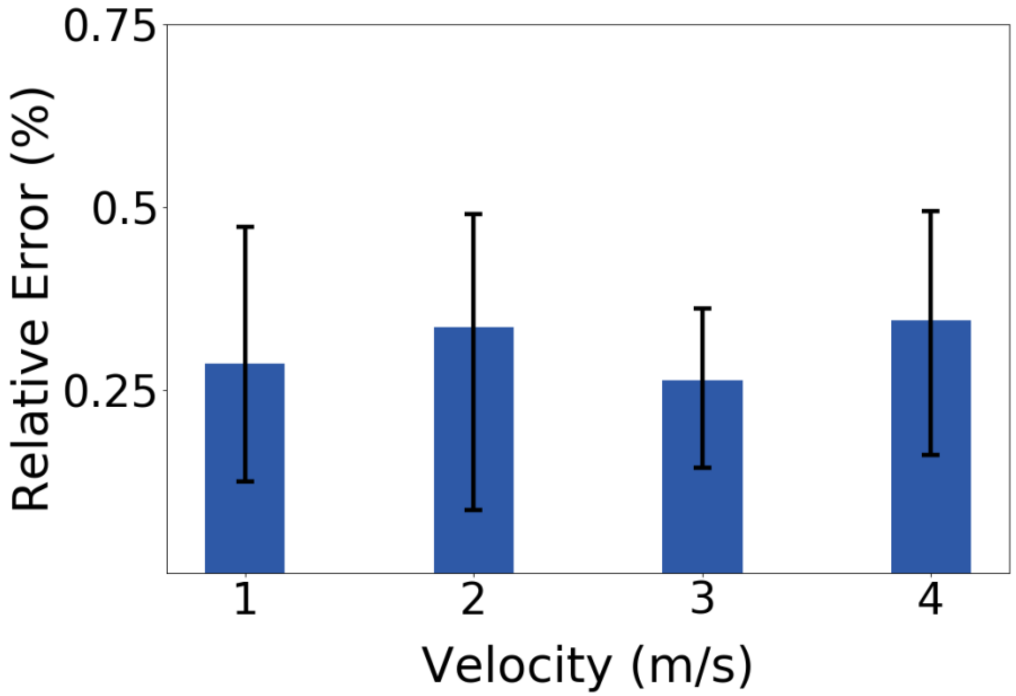




mmHawkeye works well with different UAV trajectories.

Accuracy v.s. velocity





mmHawkeye is indeed applicable with various UAV velocities.

Future work

- Multi-UAV detection

Trajectory crossover problem

- Short-range detection

Multiple PMM features

Conclusion

- The **first mmWave-based long-range** UAV detection approach.

- Provides a tailored design based on the PMM feature to fully utilize the **low-SNR and uncertained** UAV's reflected signals for UAV detection.

- Implemented on the **commercial** device TI IWR6843ISKODS board and evaluated through experiments conducted under various settings.

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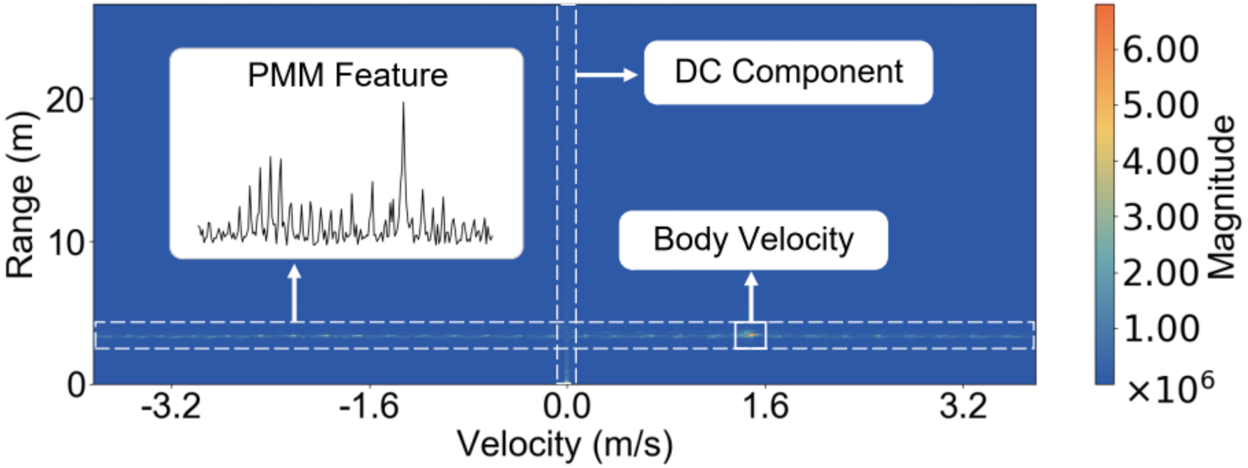
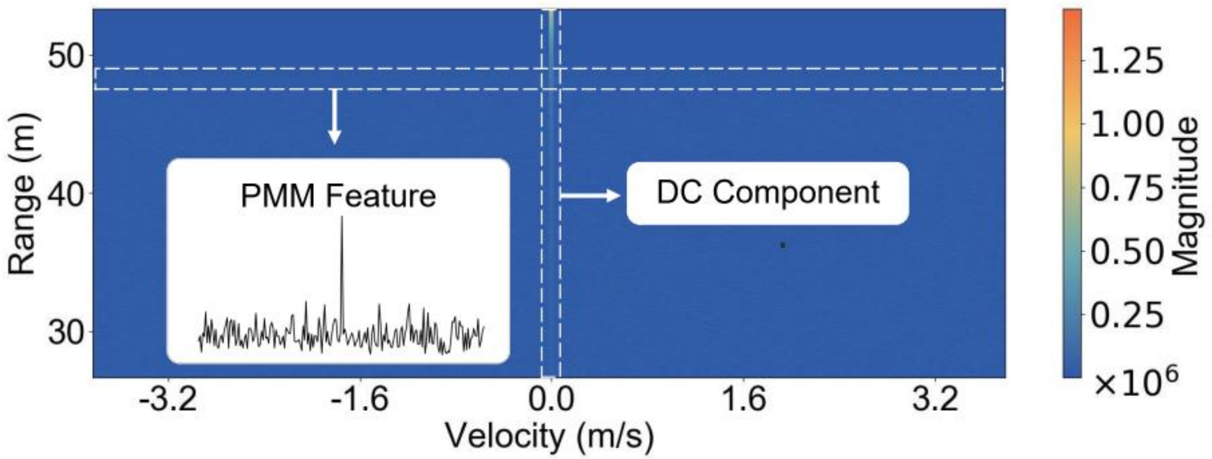
Backups

Preliminary

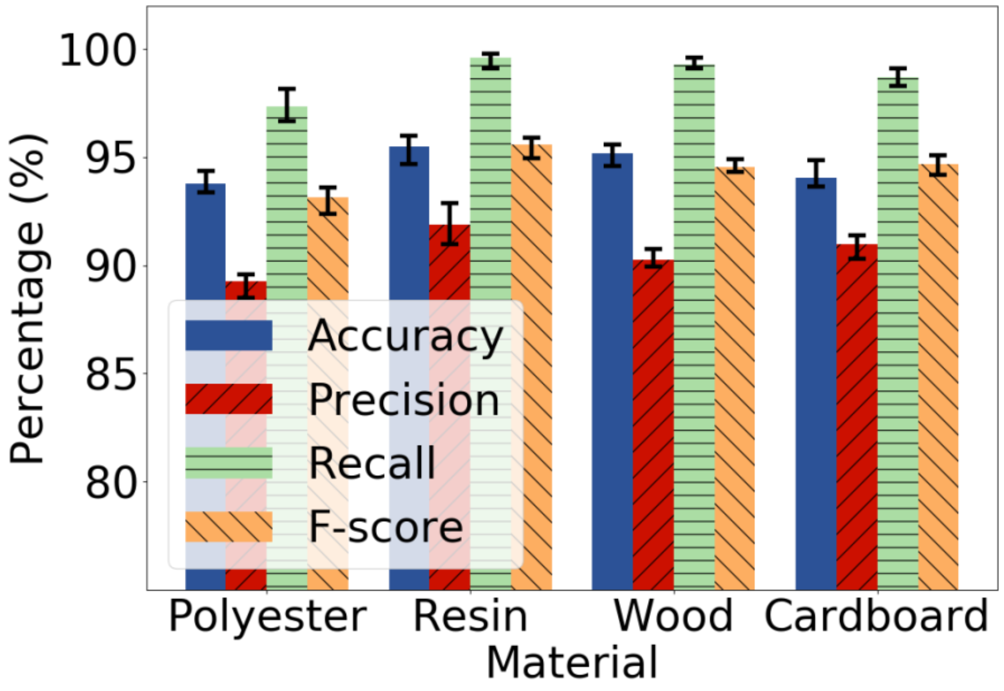


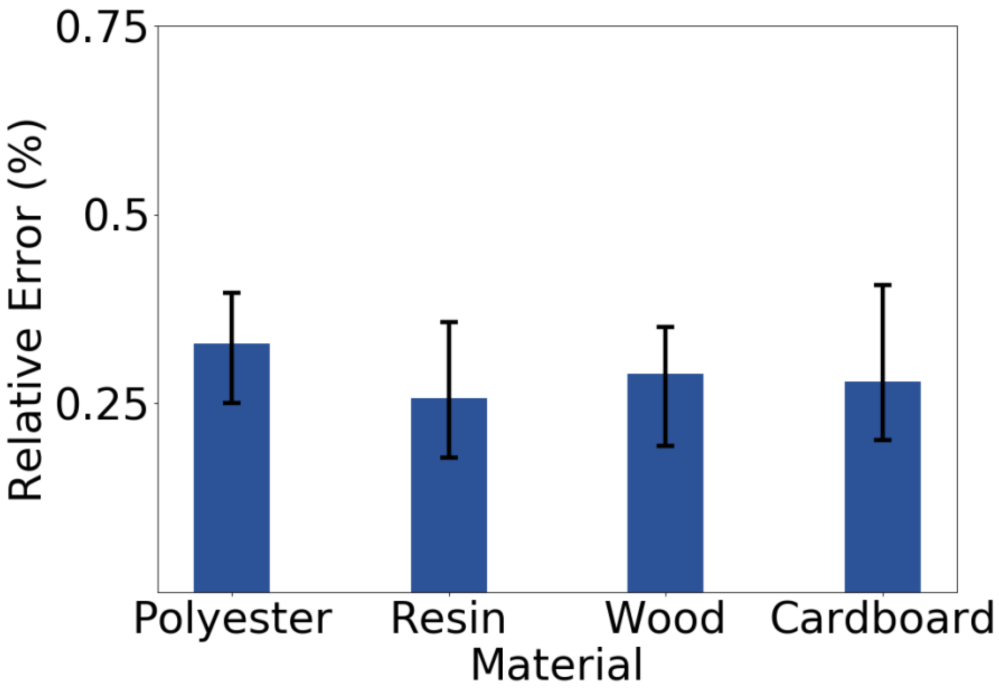
(a) The ascending UAV



(b) The hovering UAV

Accuracy v.s. obstacle





Ablation study