BatMobility 🦇:
Towards Flying Without Seeing for Autonomous Drones

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Autonomous drones enable exciting applications...

Extending wireless networks

Automated cargo delivery

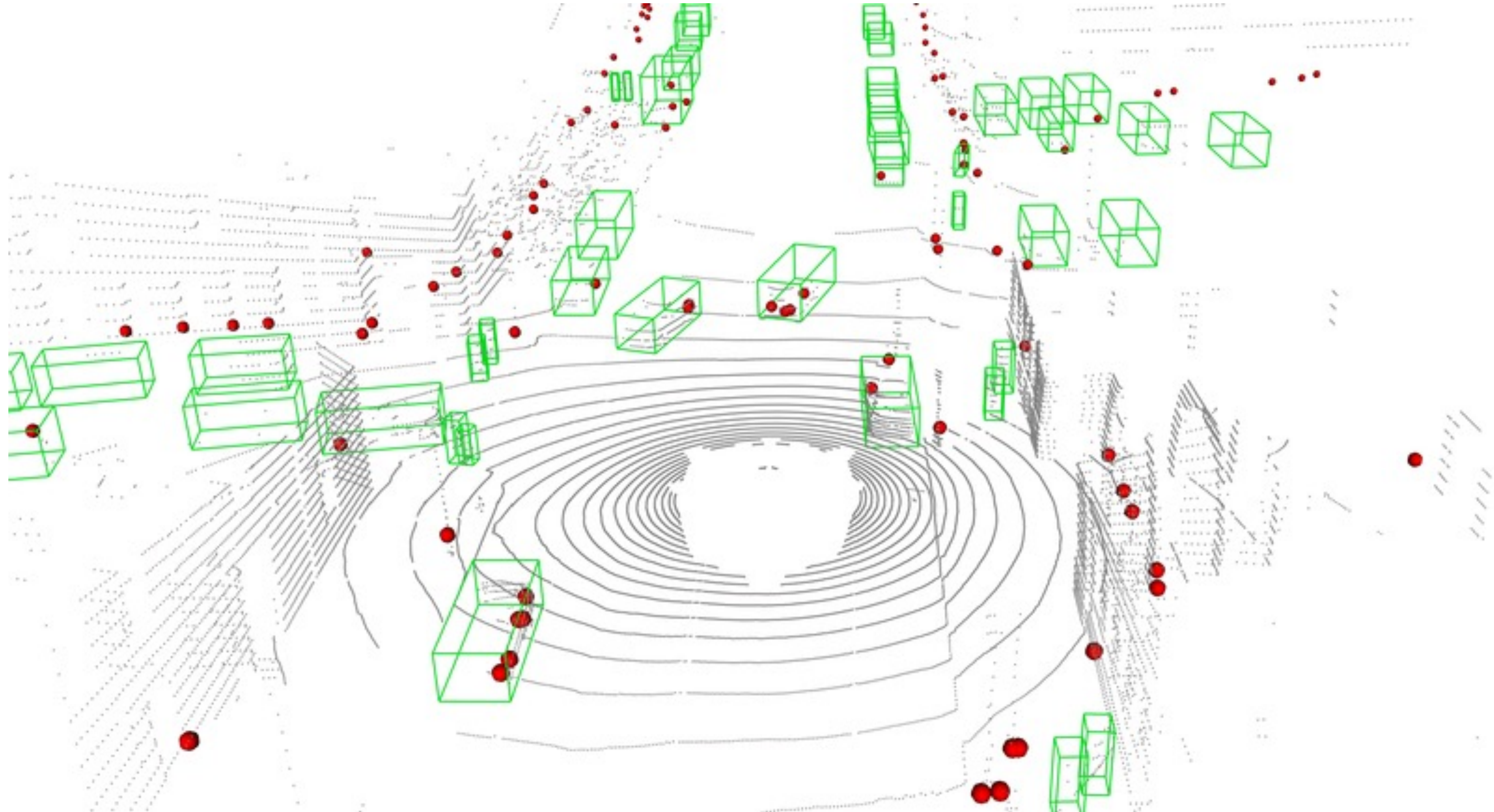**Rely on optical sensors for spatial awareness**

Surveillance and Inspection

Warehouse inventory management

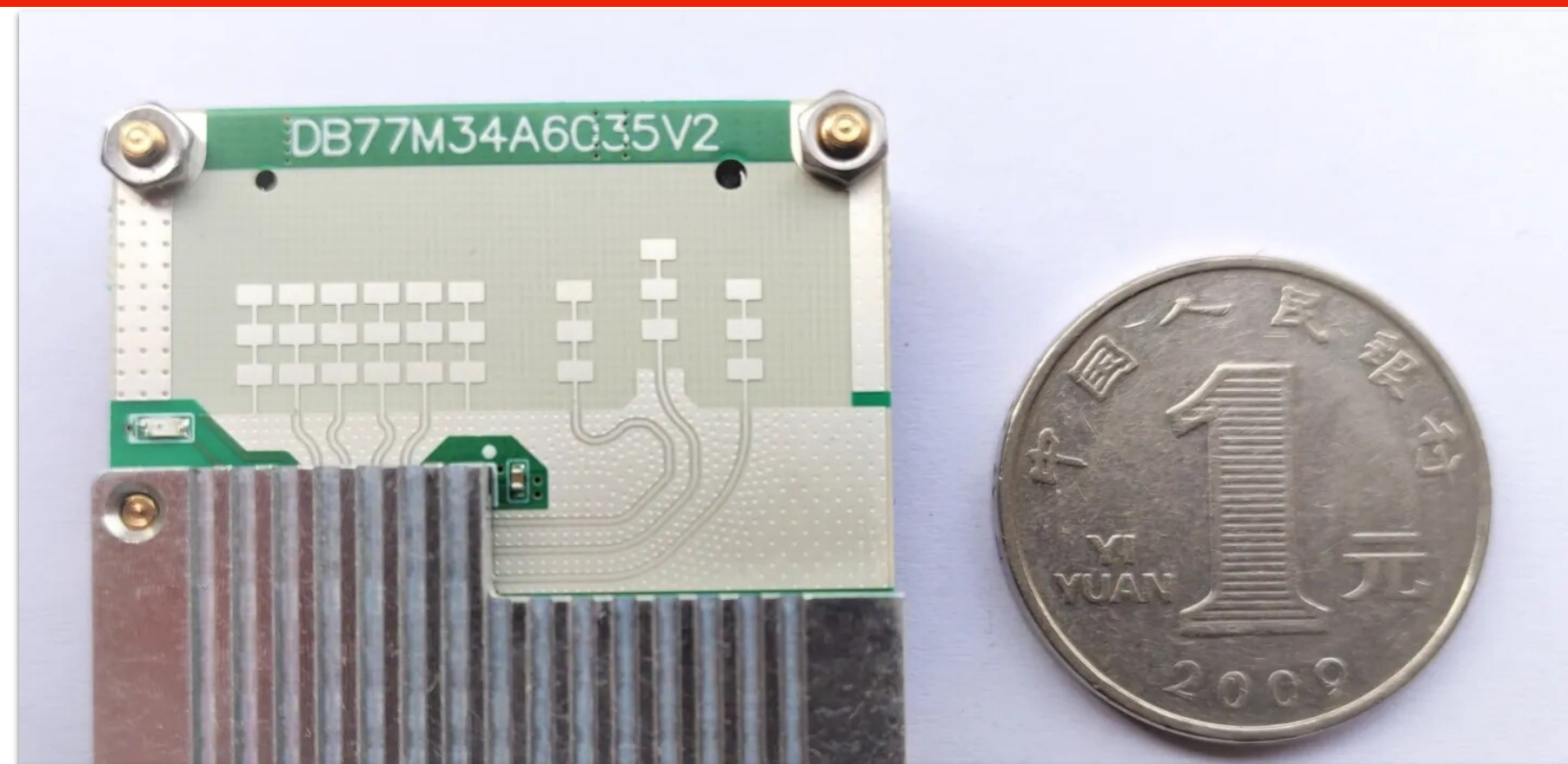# Why the hate on radar?

Yes, radar has low resolution. But...

Penetrates Fog, Smoke, Dust

Invariant to Light

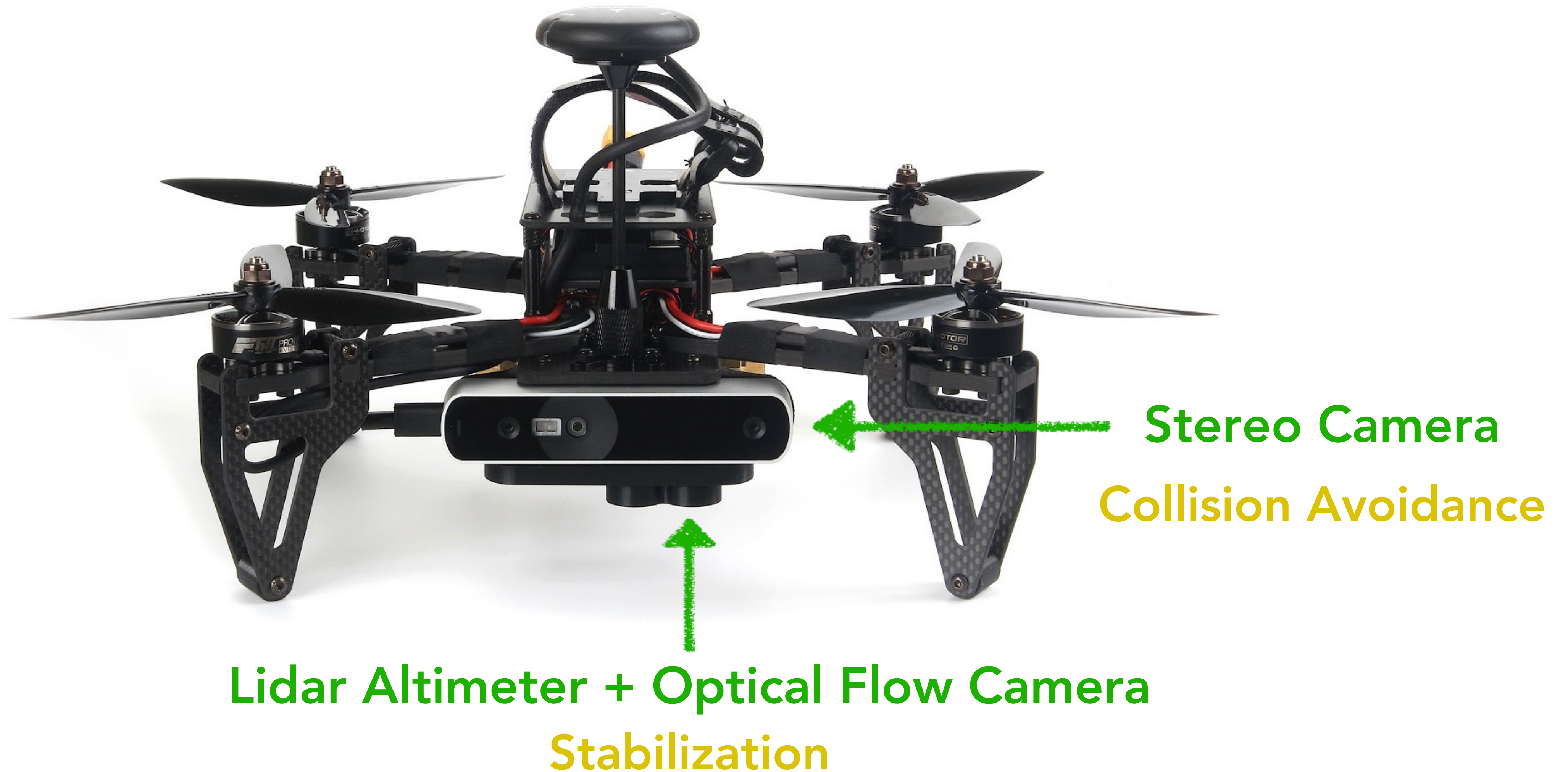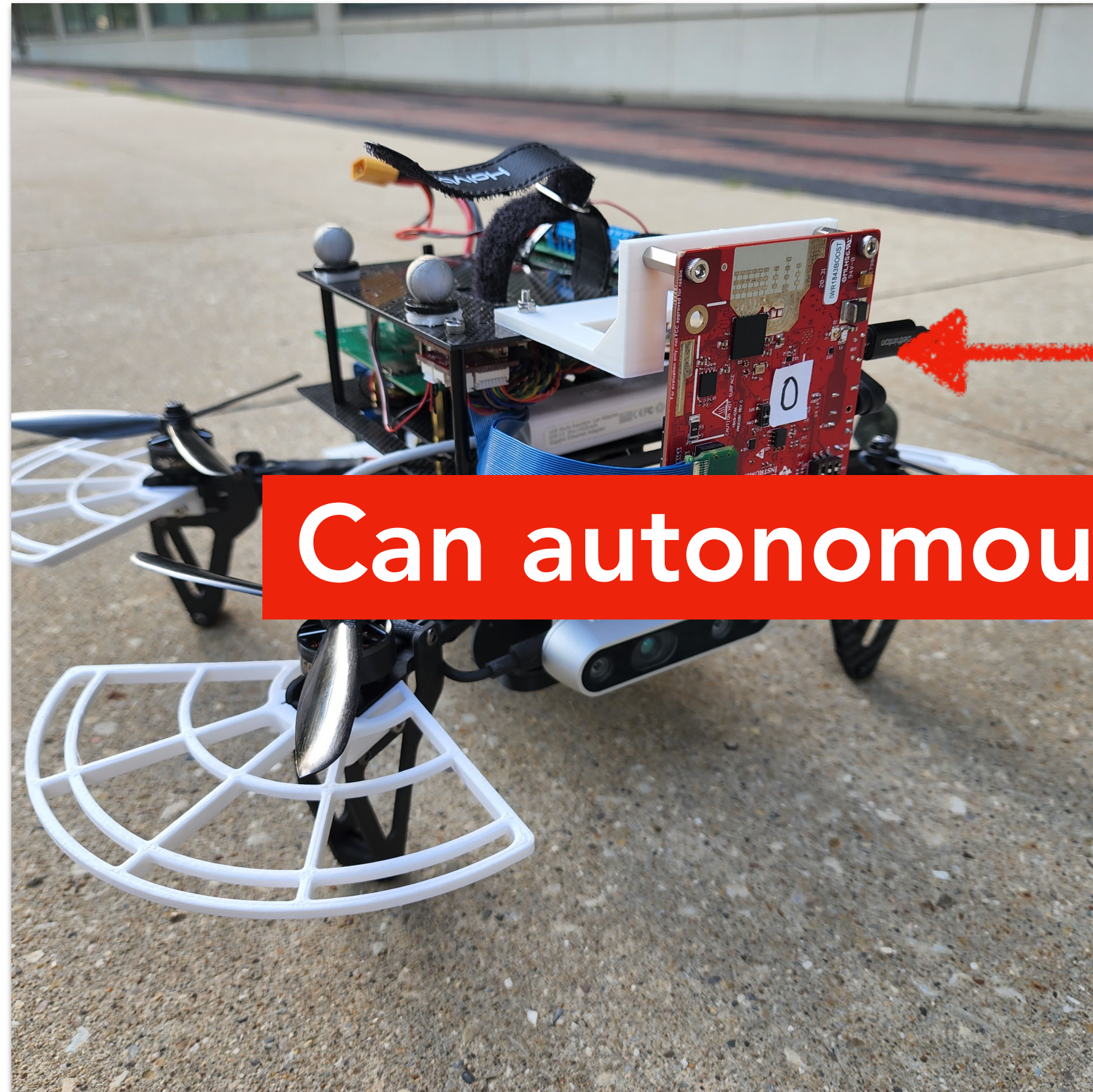**Seems like a good fit for autonomous drones 🤔**

Cheap and Small

Long Range

Radar is all you need?

Stereo Camera
Collision Avoidance

Lidar Altimeter + Optical Flow Camera
Stabilization

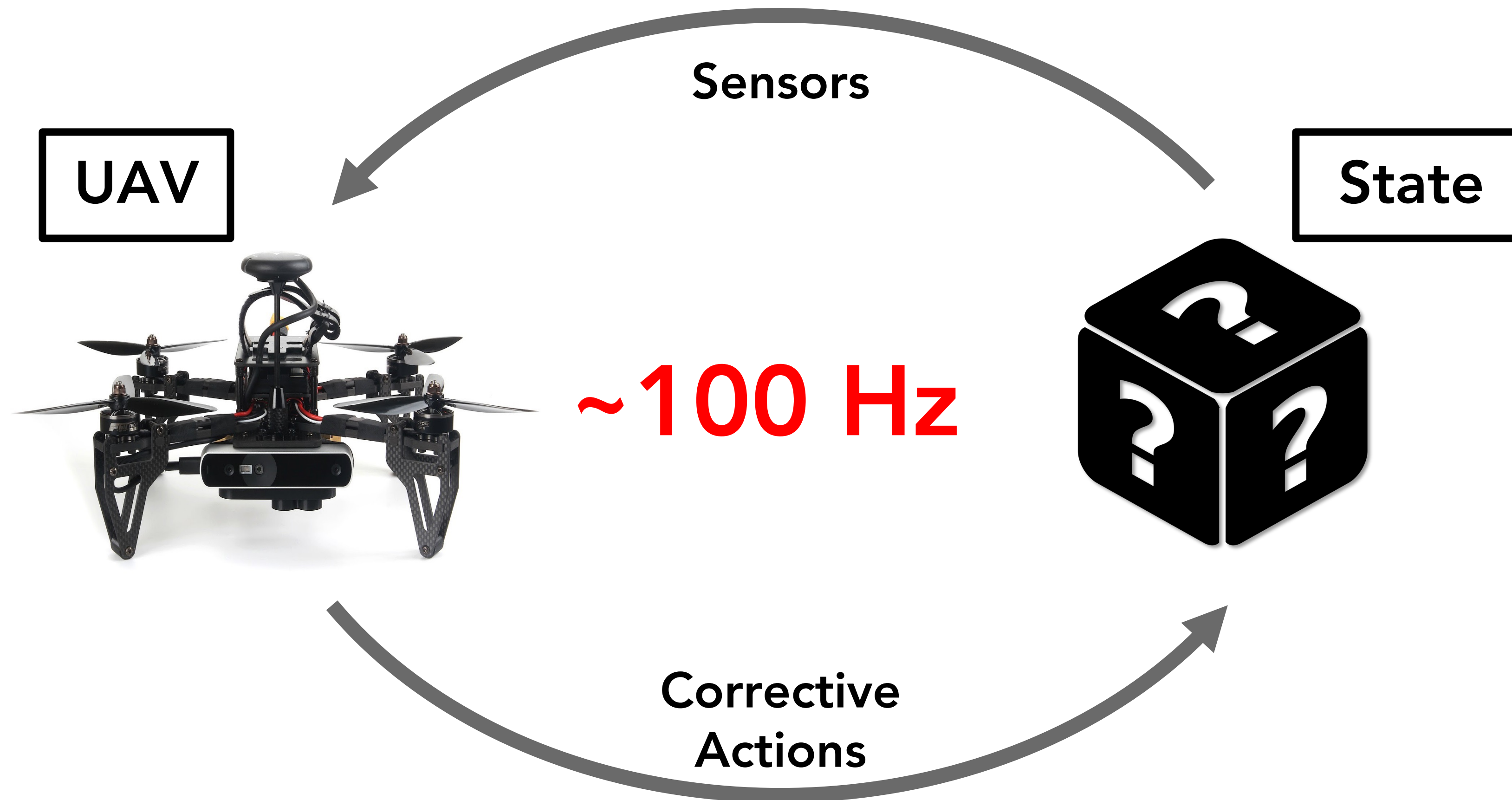# Radar is all you need?

Off-the-shelf Radars

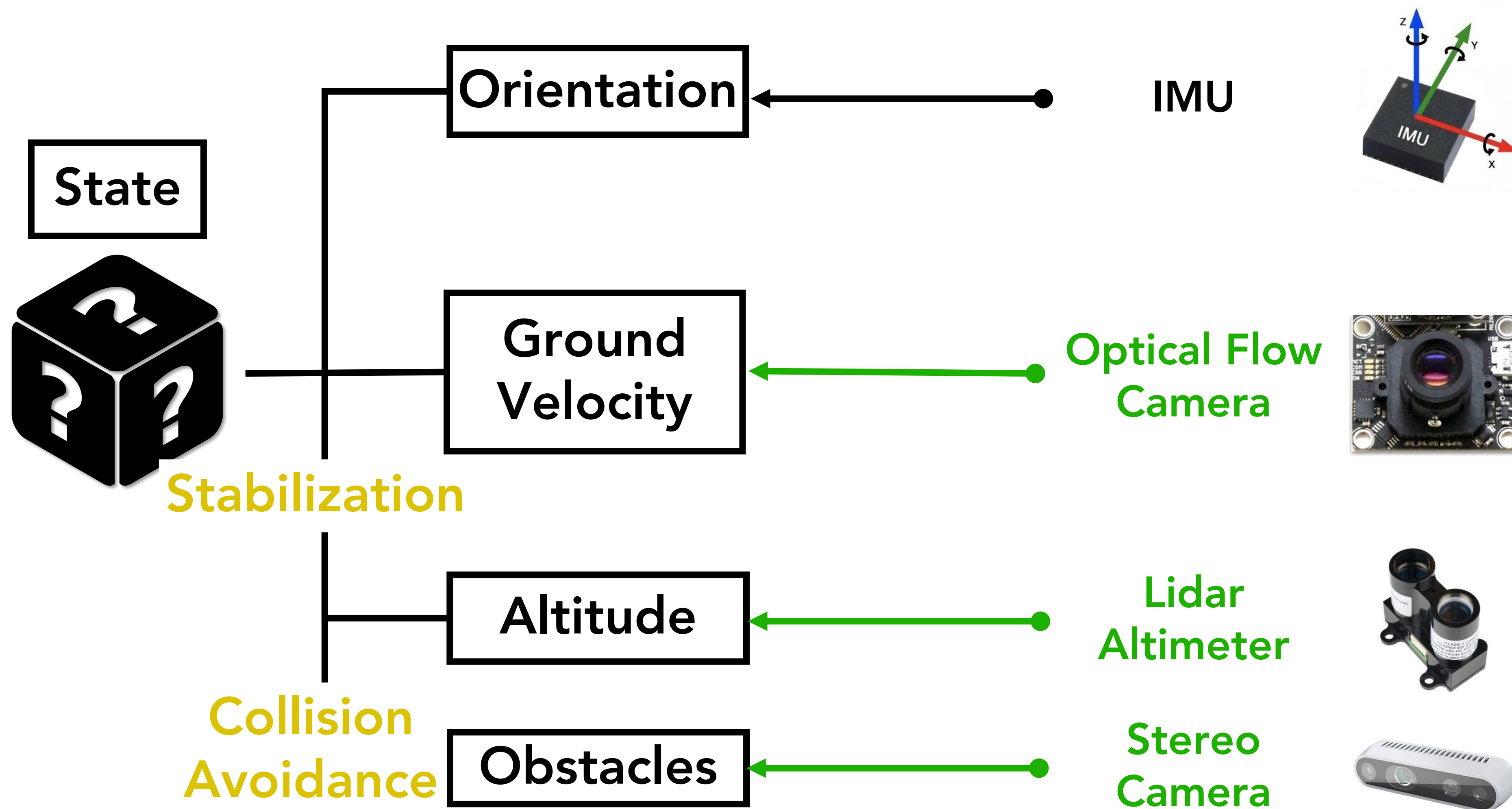Can autonomous drones fly without seeing?

Why is flying hard?

Drones are inherently unstable
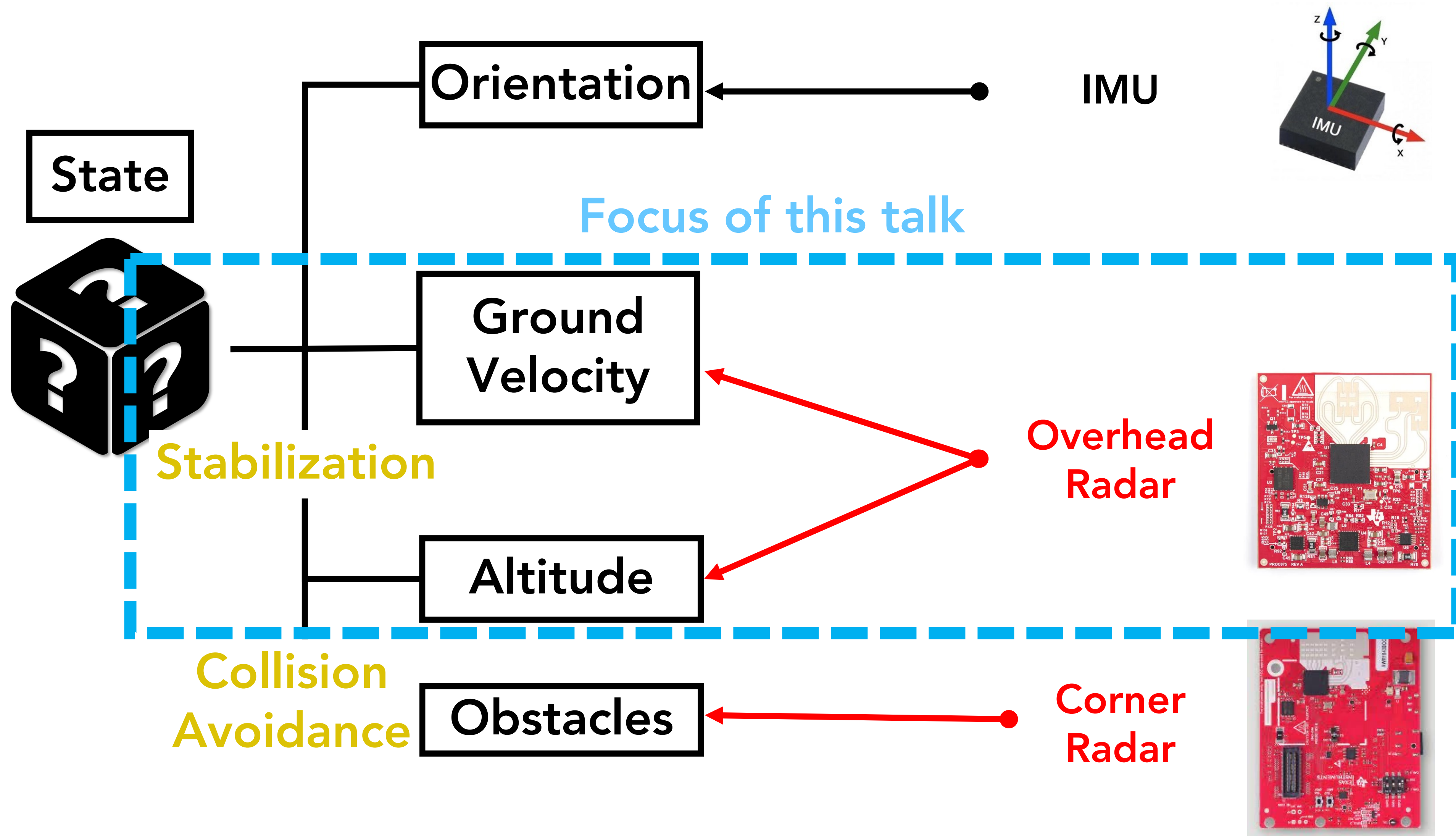
Why is flying hard?

Sensors

UAV

State

~100 Hz

Corrective
Actions

Why is flying hard?

State

Orientation — IMU

Ground Velocity — Optical Flow Camera

Stabilization

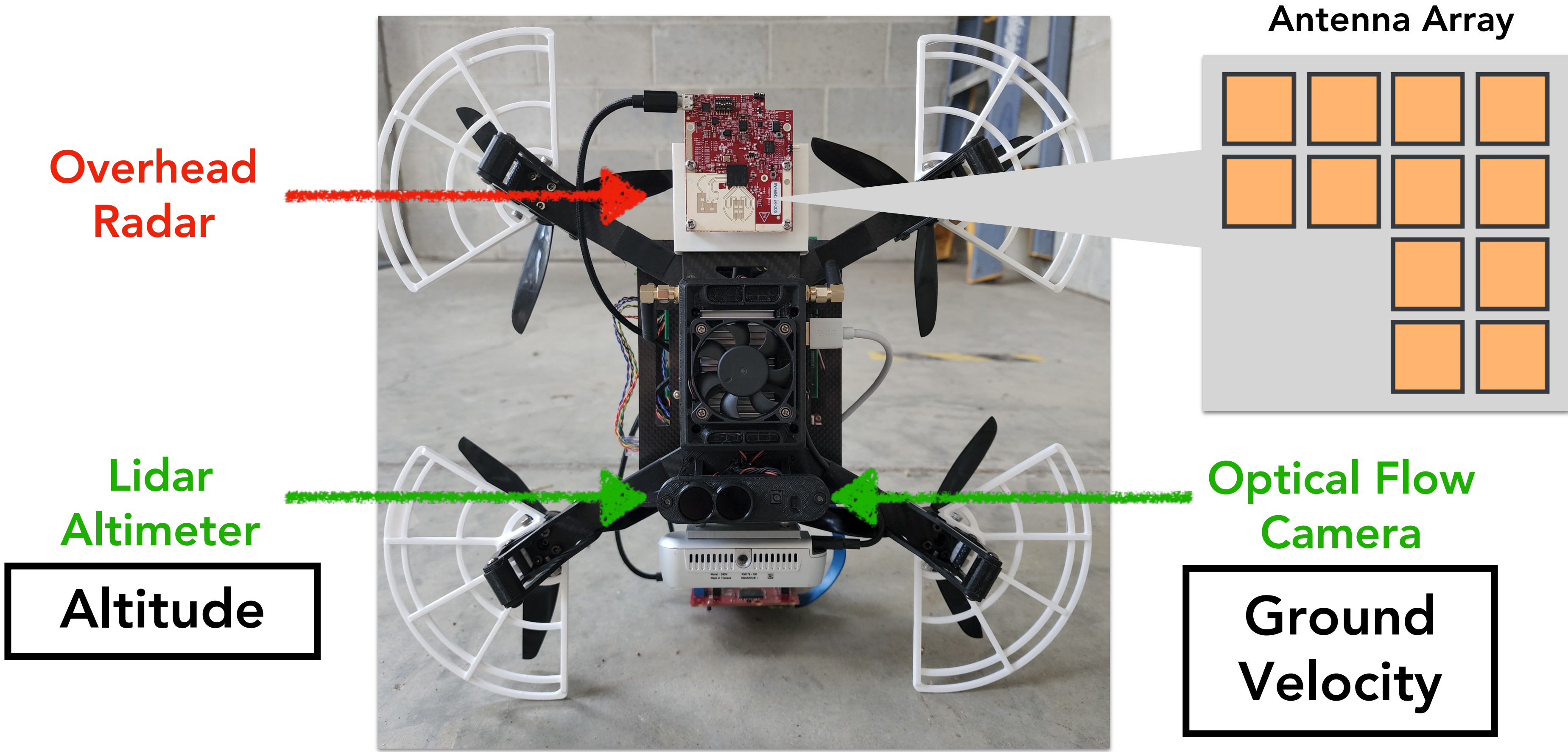Altitude — Lidar Altimeter

Collision Avoidance — Obstacles — Stereo Camera

BatMobility Overview

This Talk: Stabilize the Drone with 1 Radar

Overhead Radar

Antenna Array

Lidar Altimeter

Altitude

Optical Flow Camera

Ground Velocity

How to get ground velocity from radar?

Optical Methods Rely on Correspondences

Optical Flow

t $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $t + \Delta t$

Optical Methods Rely on Correspondences
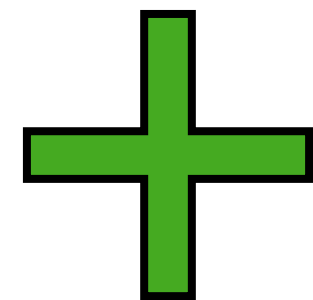
Optical Flow

Scan Matching
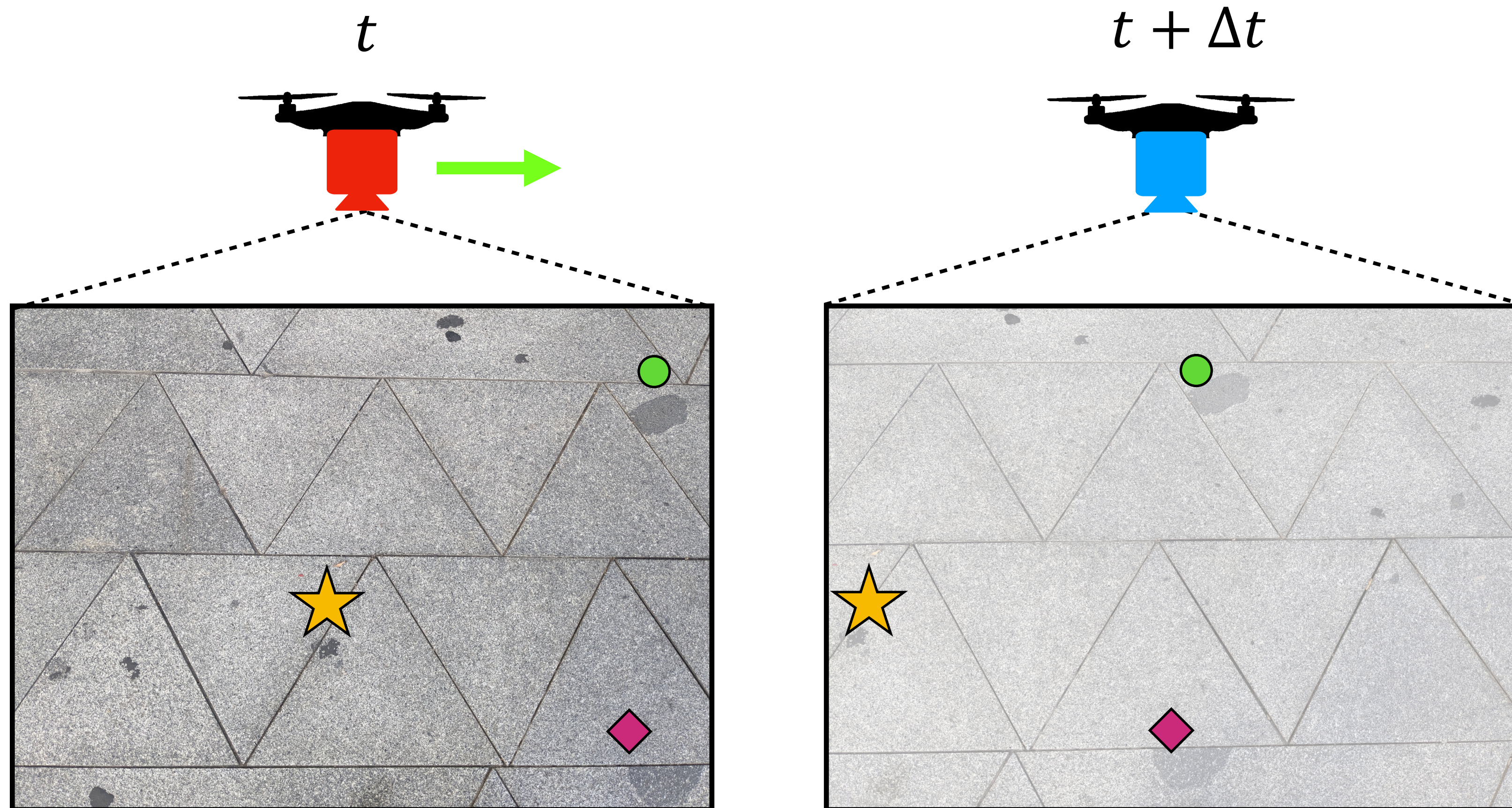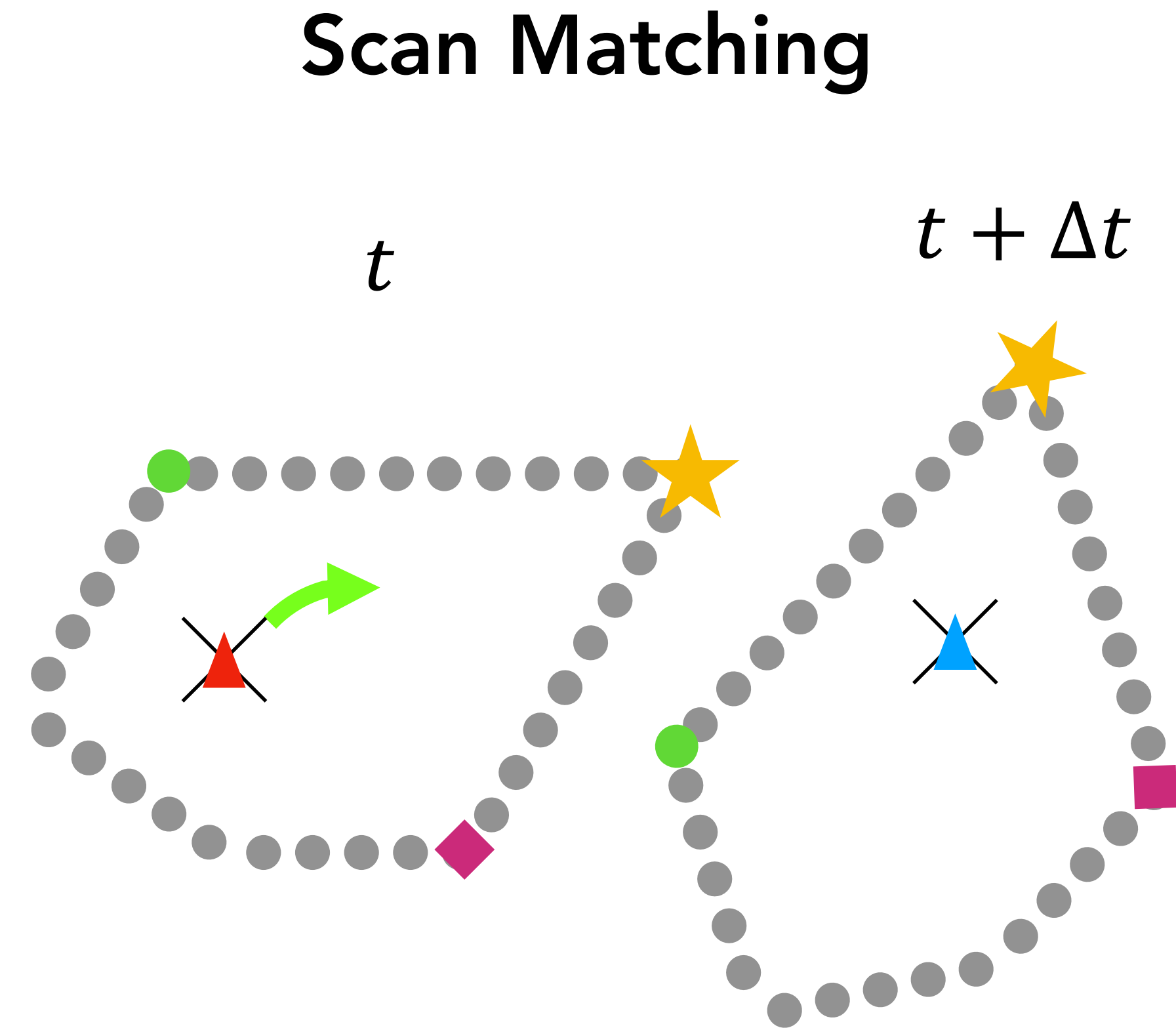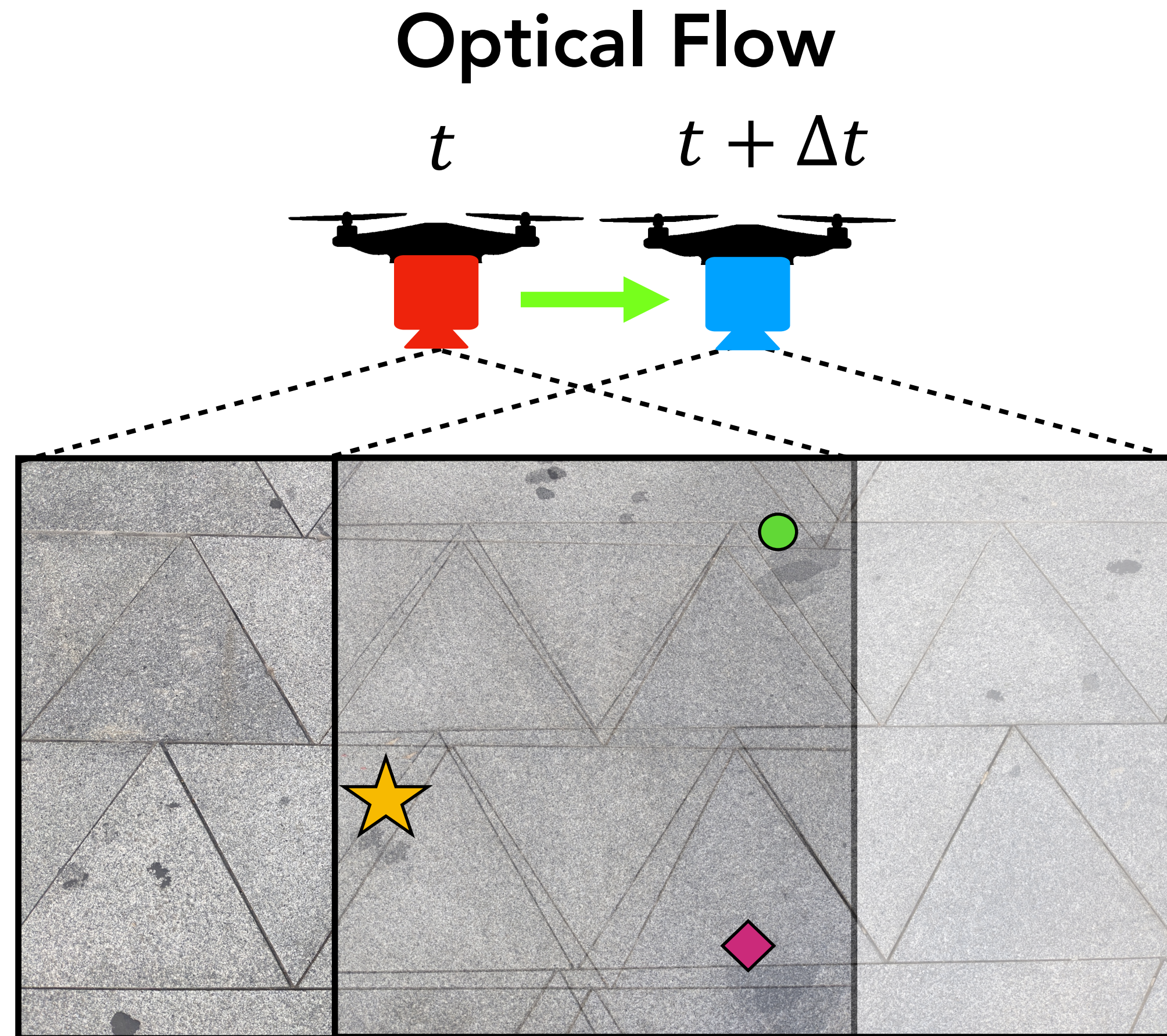
Works very well with optical sensors!

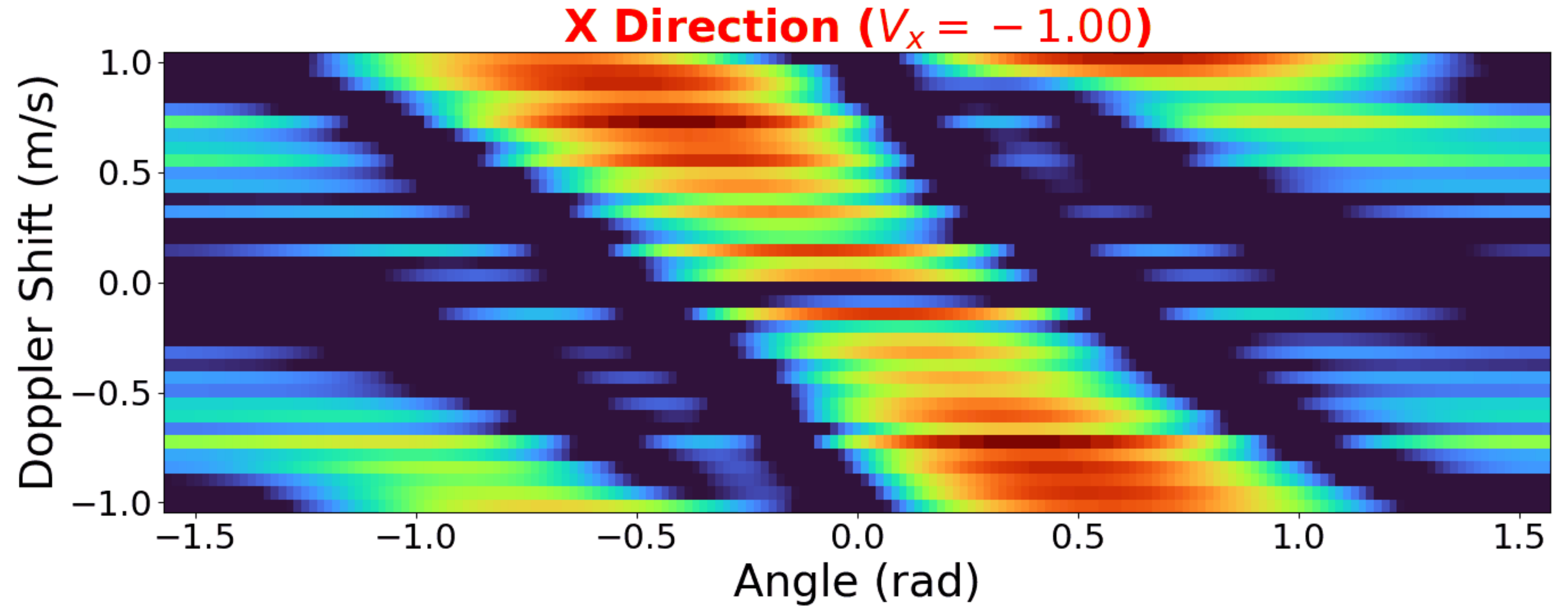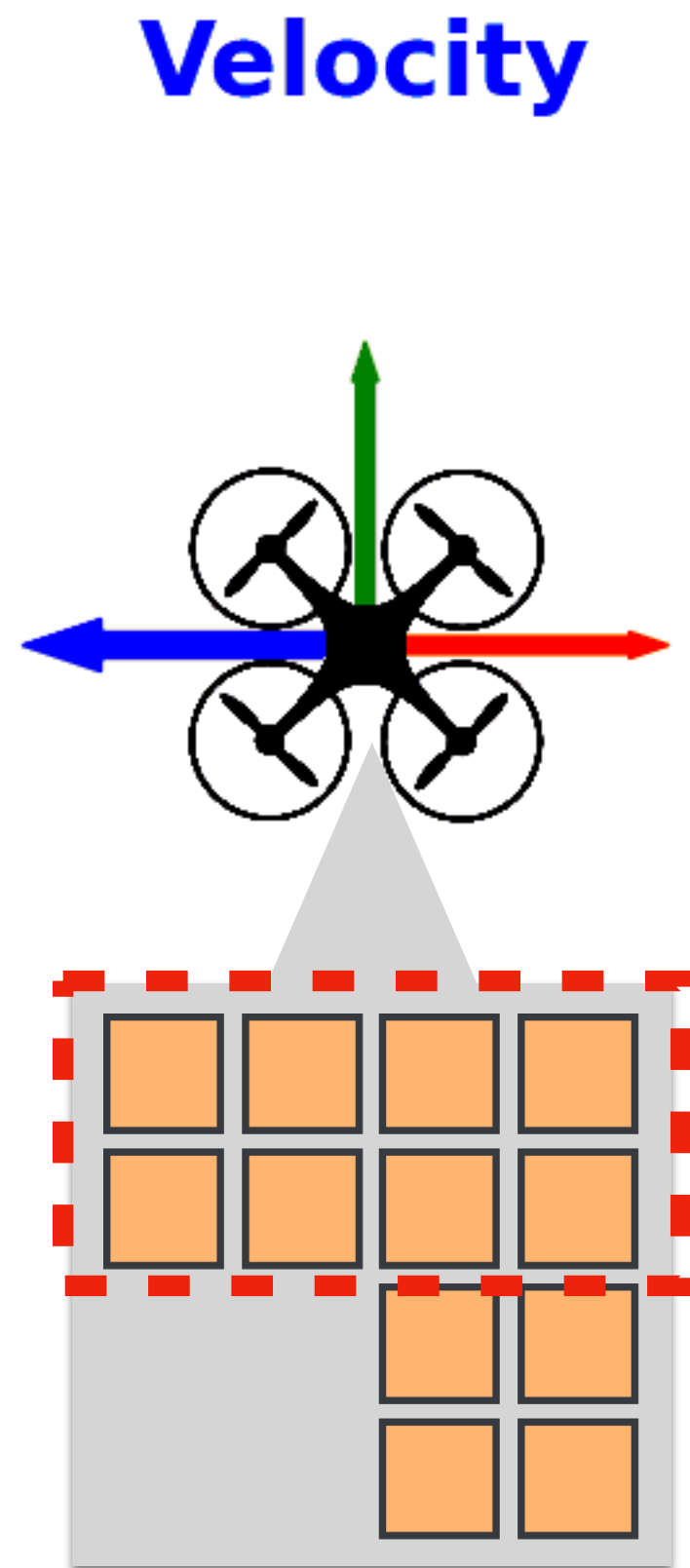# Why doesn't this work with radar?

Radar

t

$t + \Delta t$

v

No correspondences
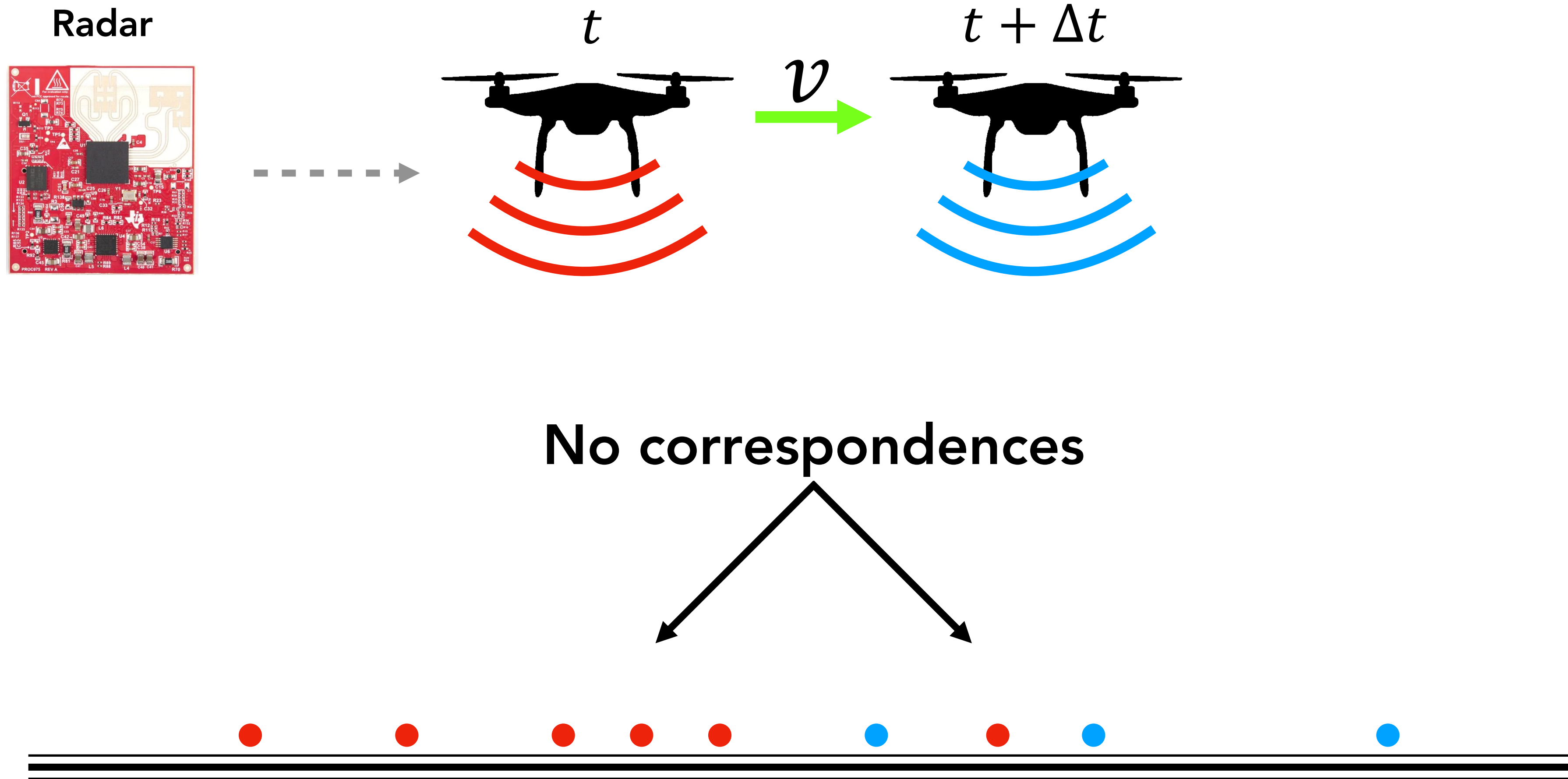
Our Approach: Doppler Shift

Surface-Parallel Doppler Shift

Radar

v

θ $v\sin\theta$

Diffuse @ mmWave frequencies!

Surface-Parallel Doppler Shift

Velocity

X Direction ($V_x = -1.00$)
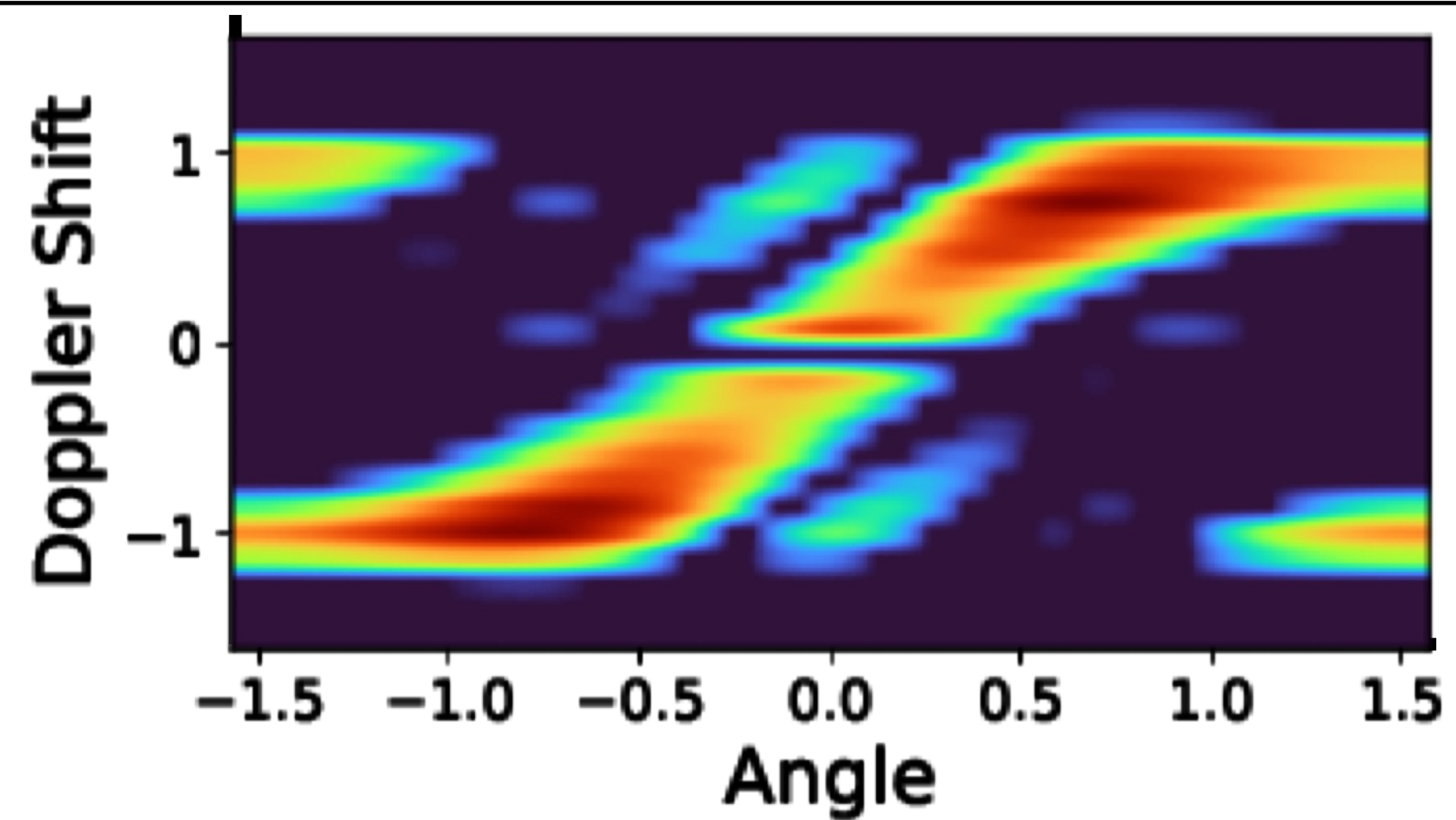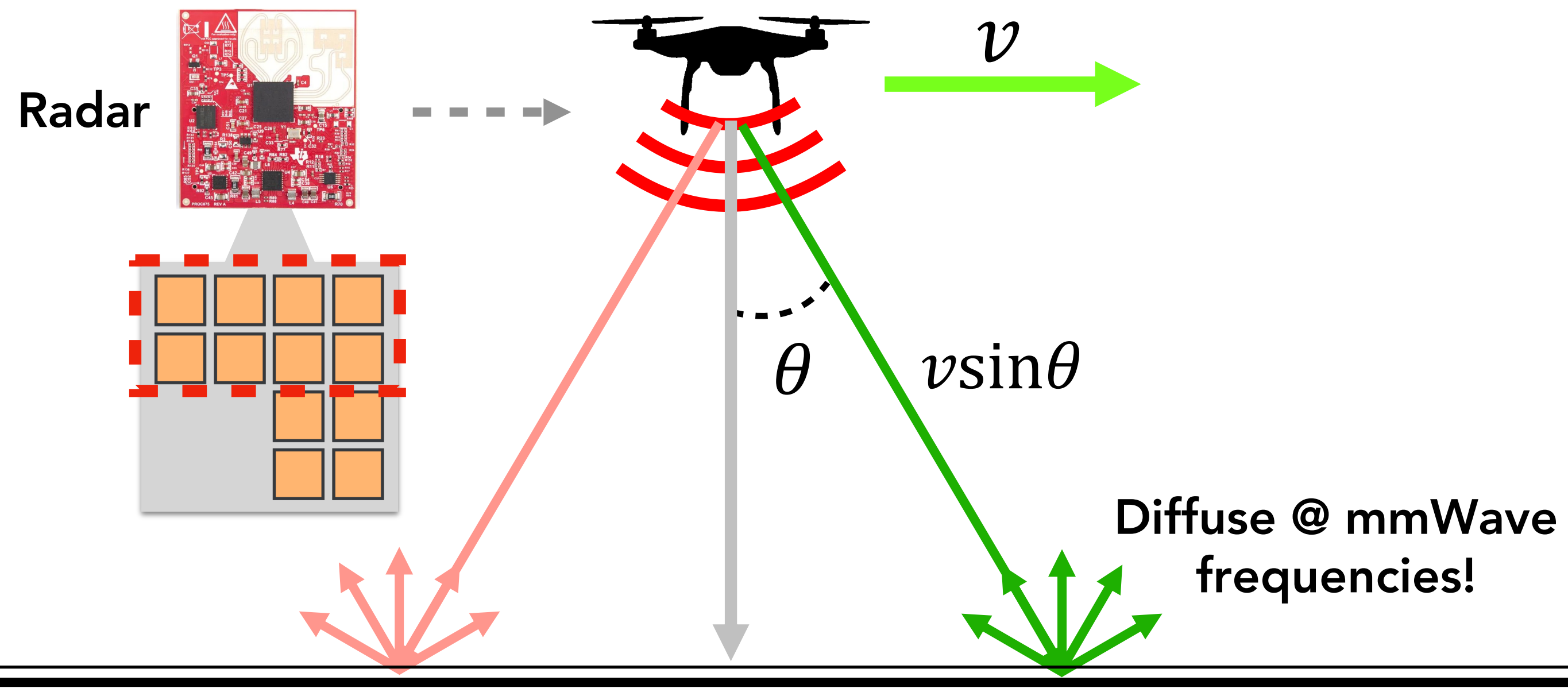
Magnitude correlated with velocity

Surface-Parallel Doppler Shift

90 degree phase shift
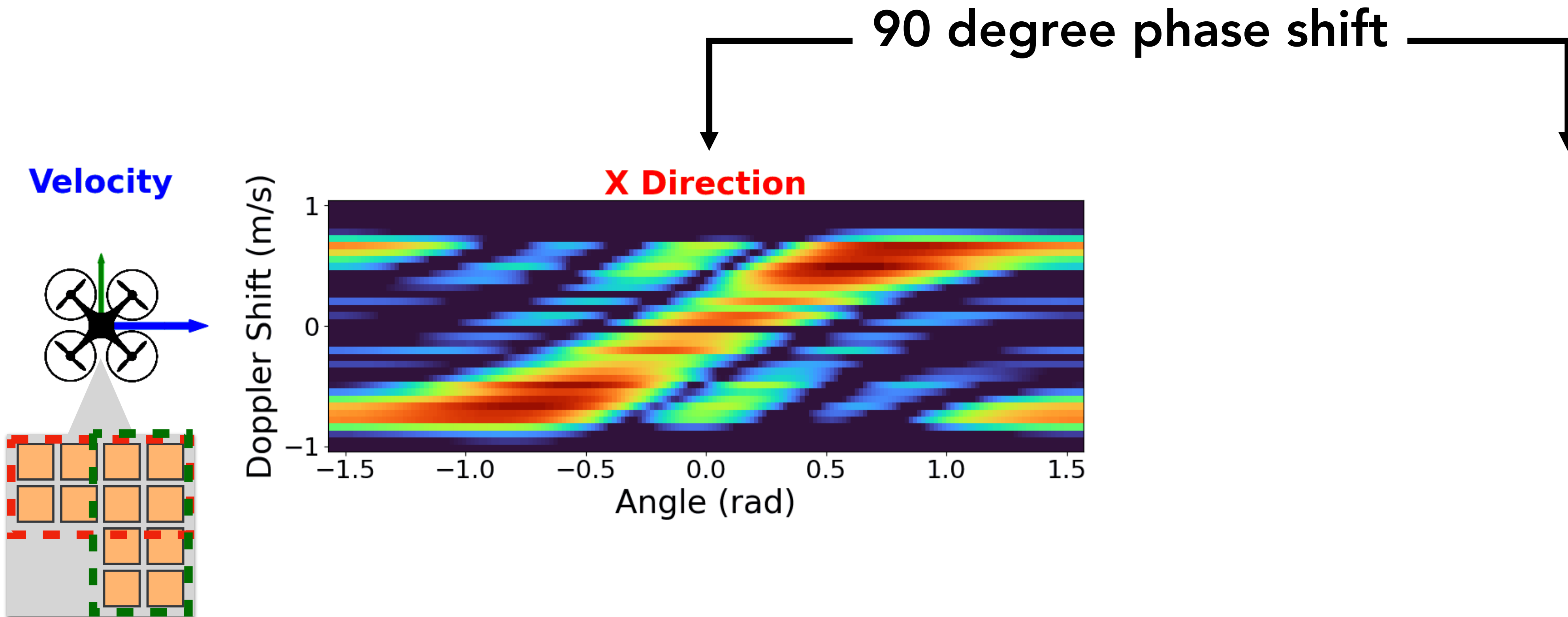
Velocity

Combine X and Y to find 2D velocity
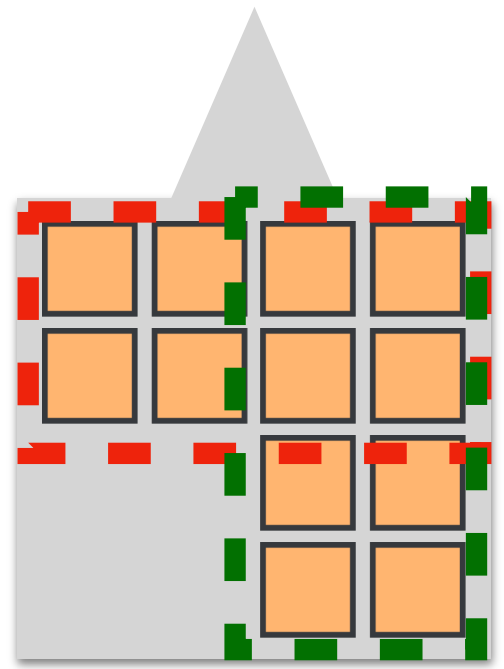
What does it look like in reality?
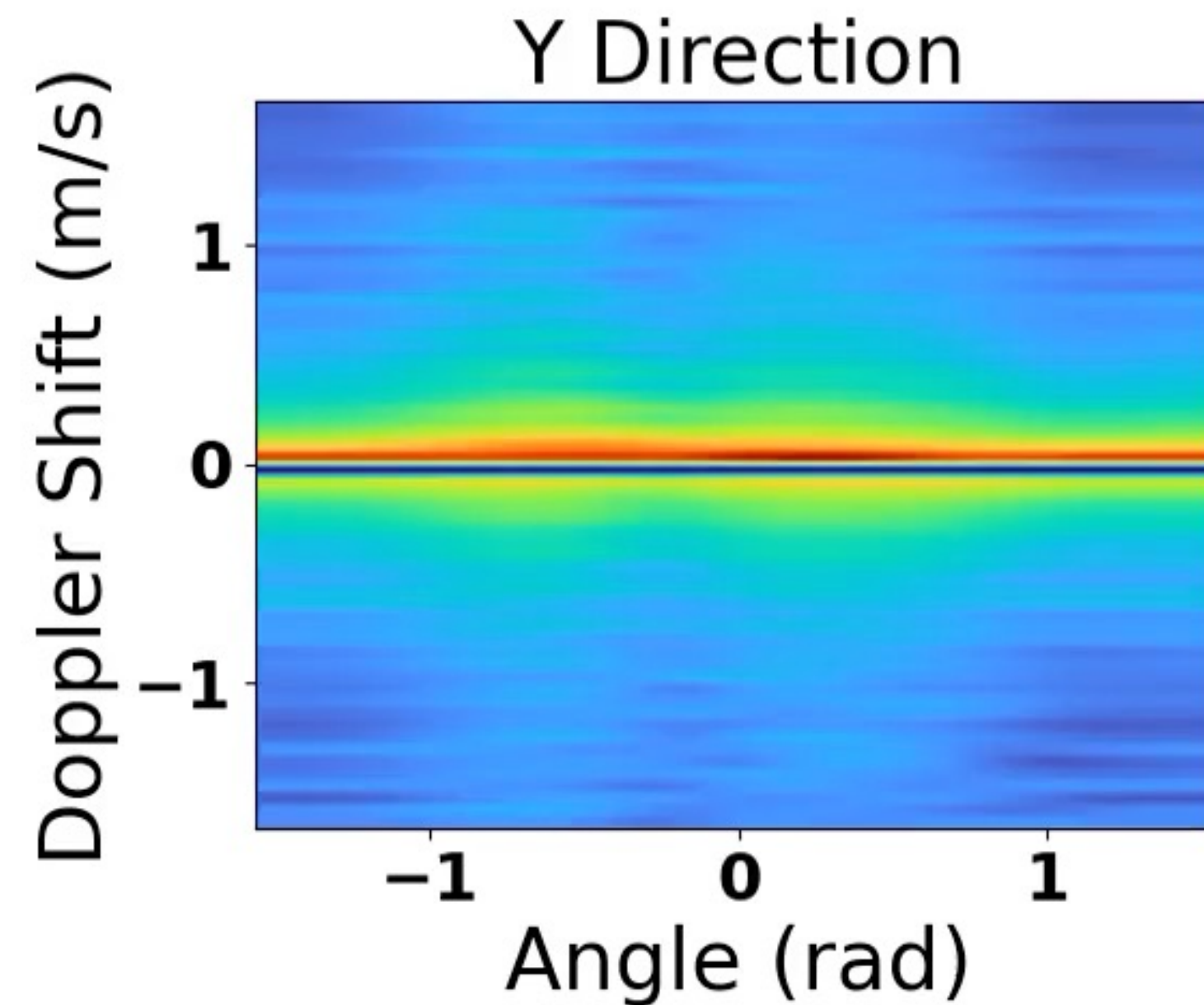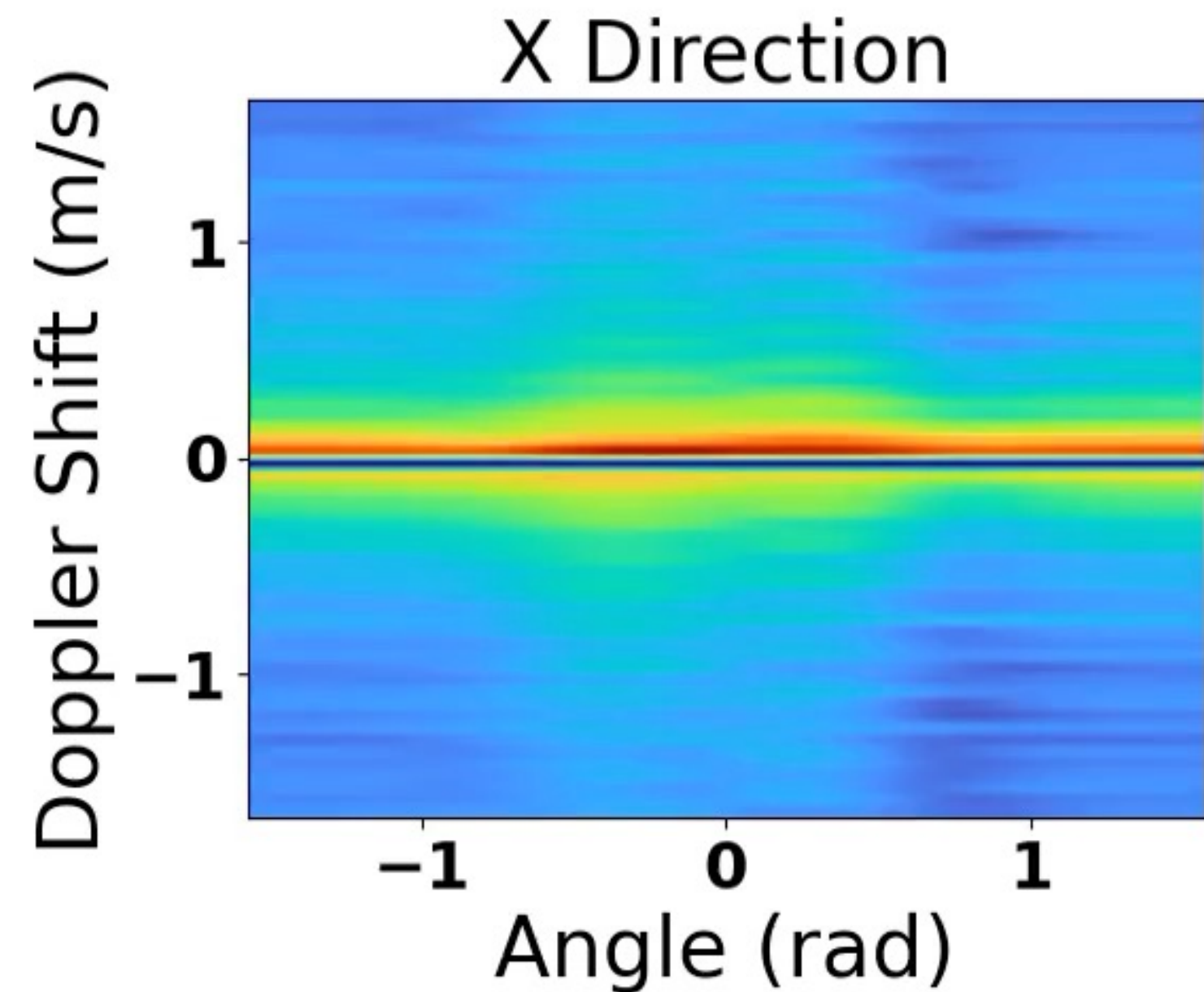
Heatmaps cluttered by
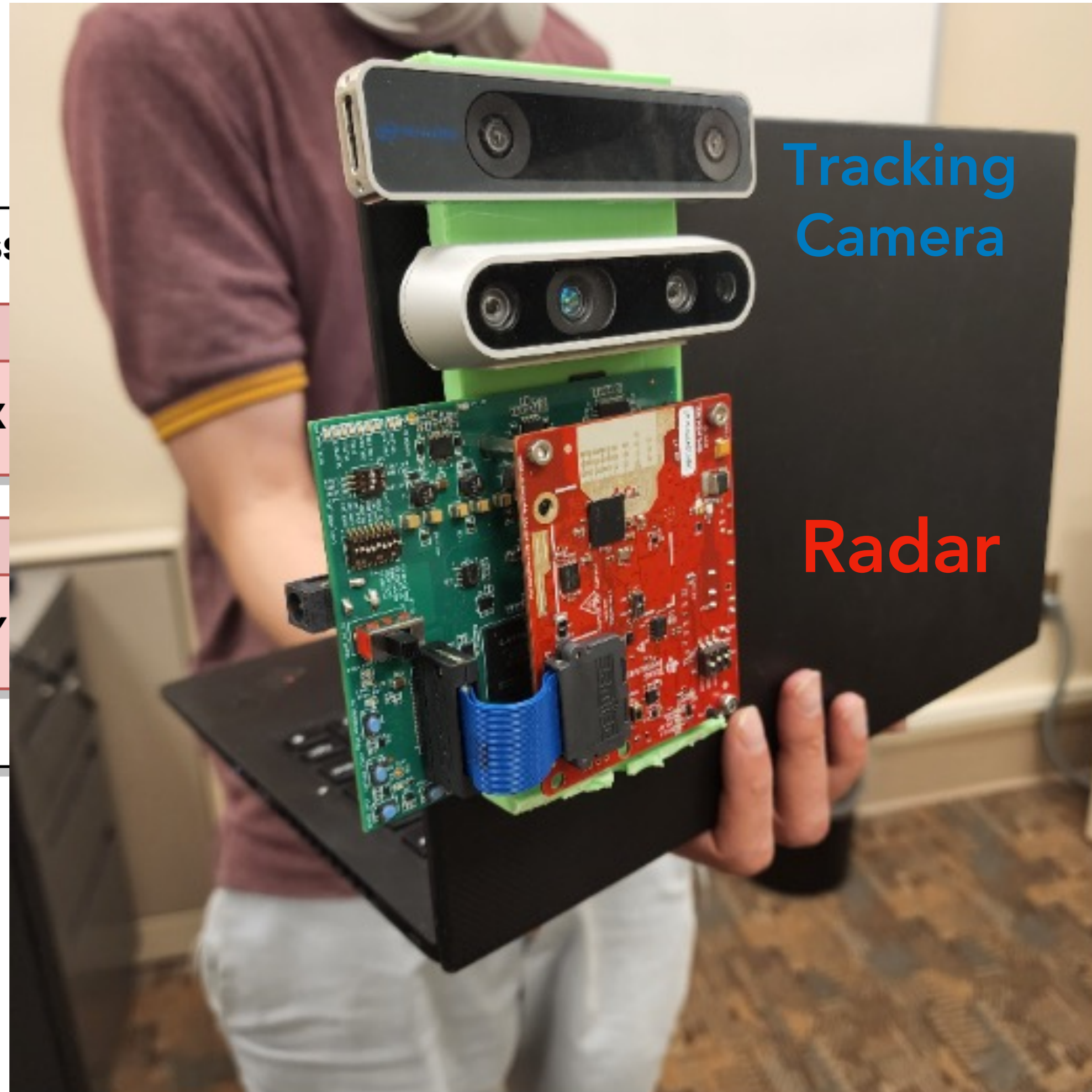- Noise
- Multipath
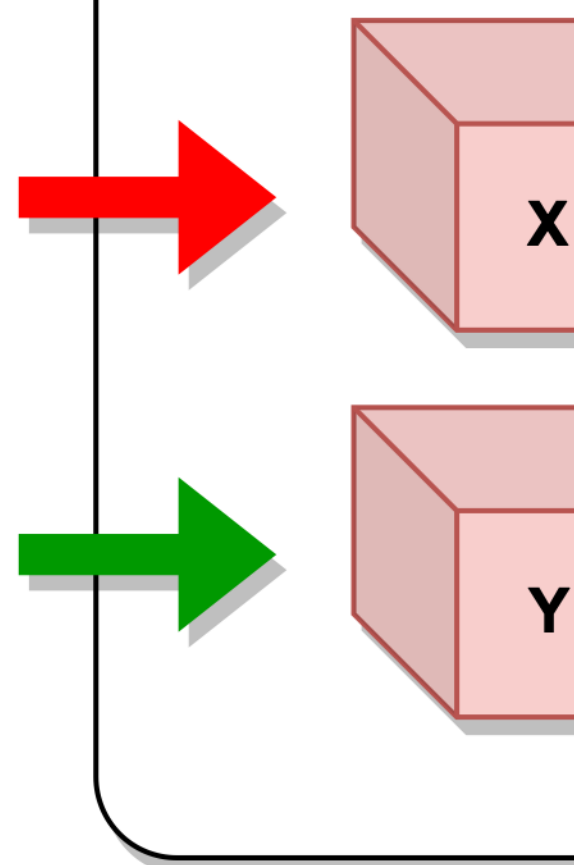- Surface Reflectivity
- Surface Specularity

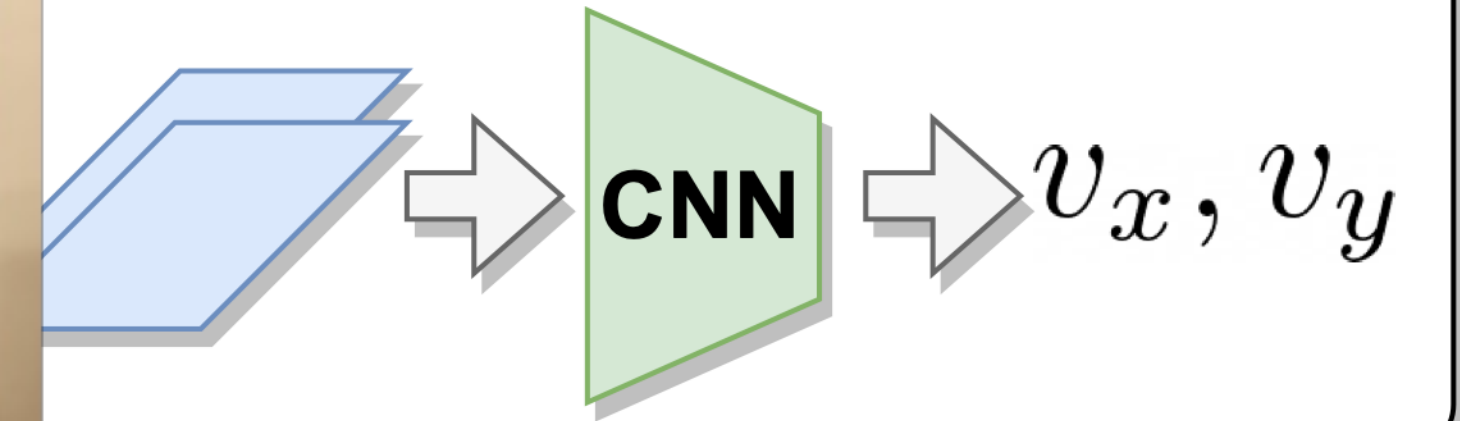**Need some way to cut through the clutter**

Radio Flow CNN

Antenna Array

Preproces...

X

Y

...erence

CNN

v_x, v_y

Tracking Camera

Radar
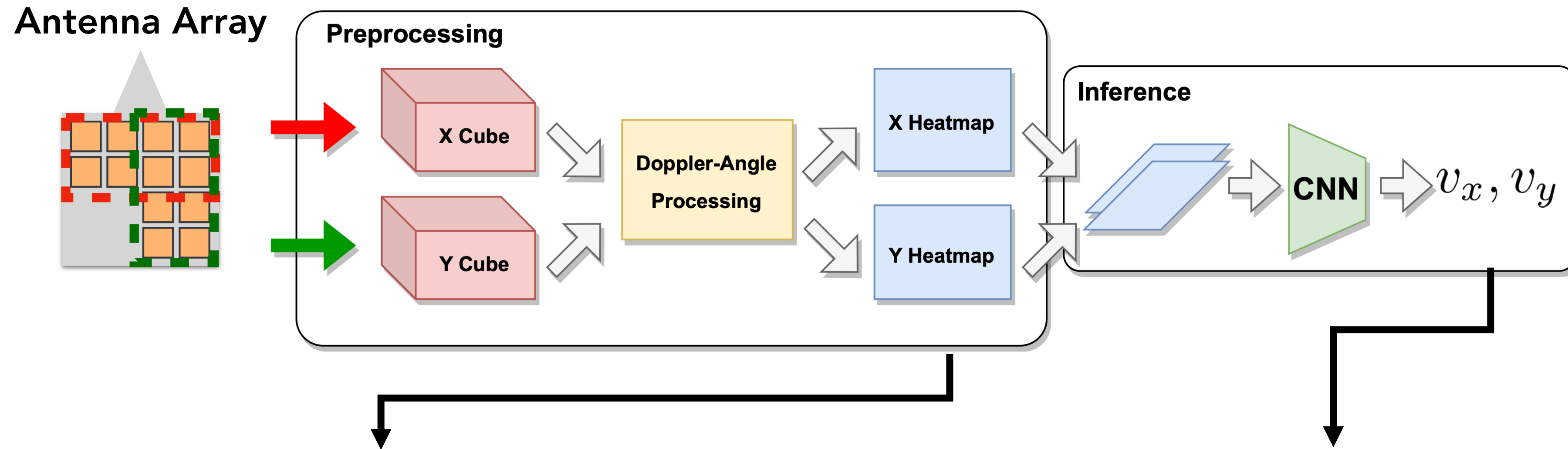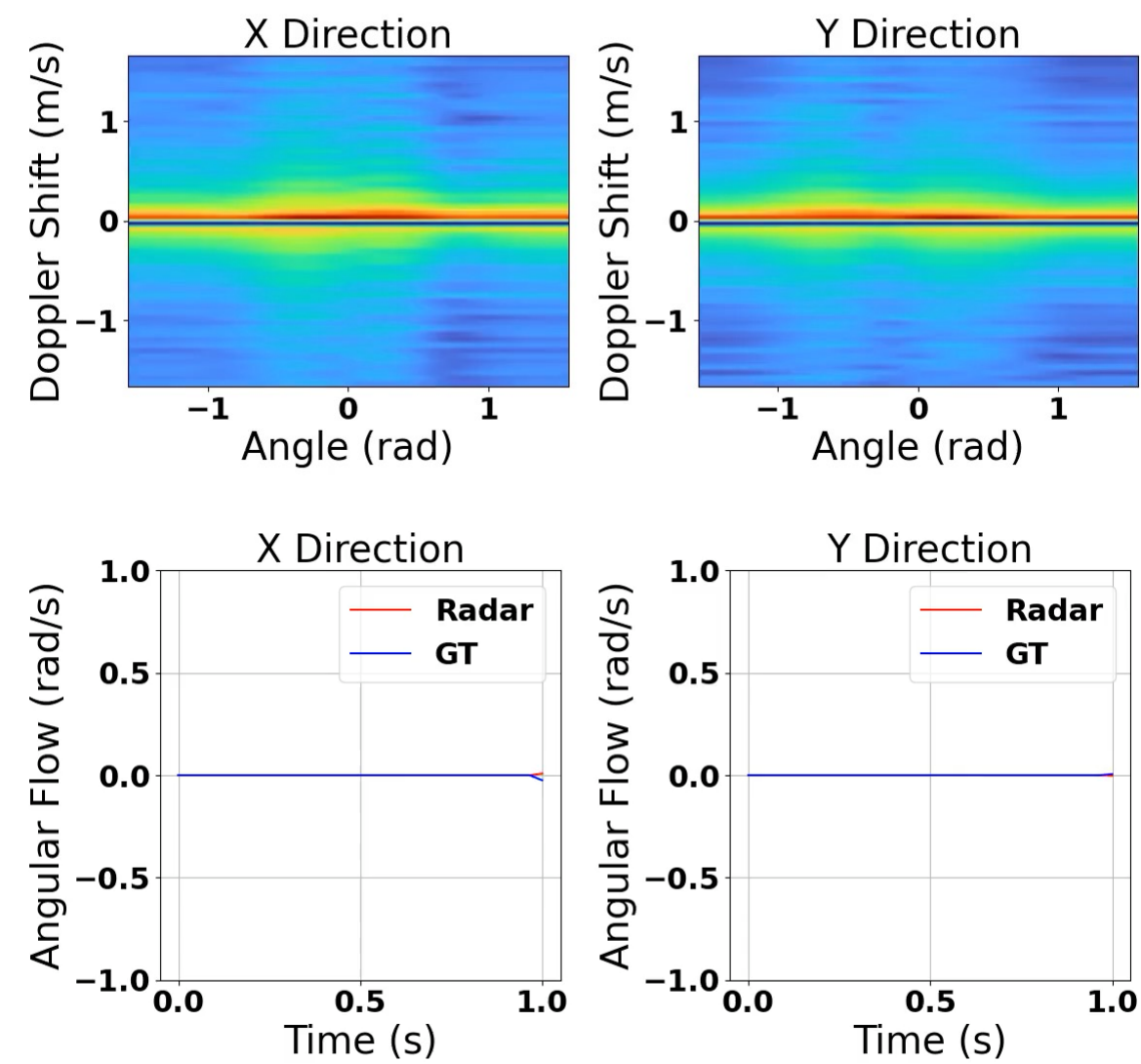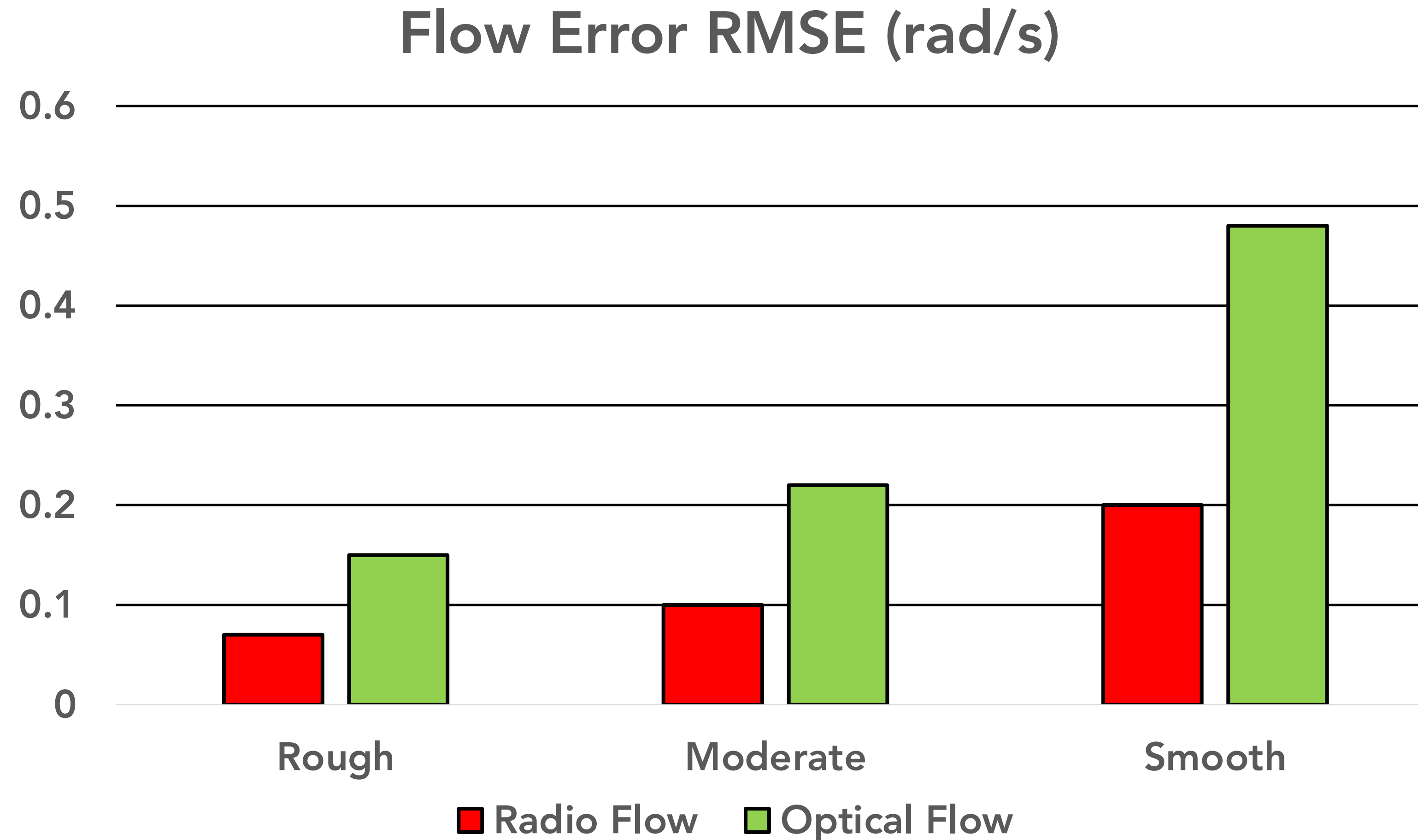
Radio Flow CNN

Does this generalize across surfaces?

Grass

Difficulty increases with surface smoothness

Does this generalize across surfaces?

Flow Error RMSE (rad/s)

Rough | Moderate | Smooth

■ Radio Flow   ■ Optical Flow

Difficulty increases with surface smoothness

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Plug-and-play into off-the-shelf drone
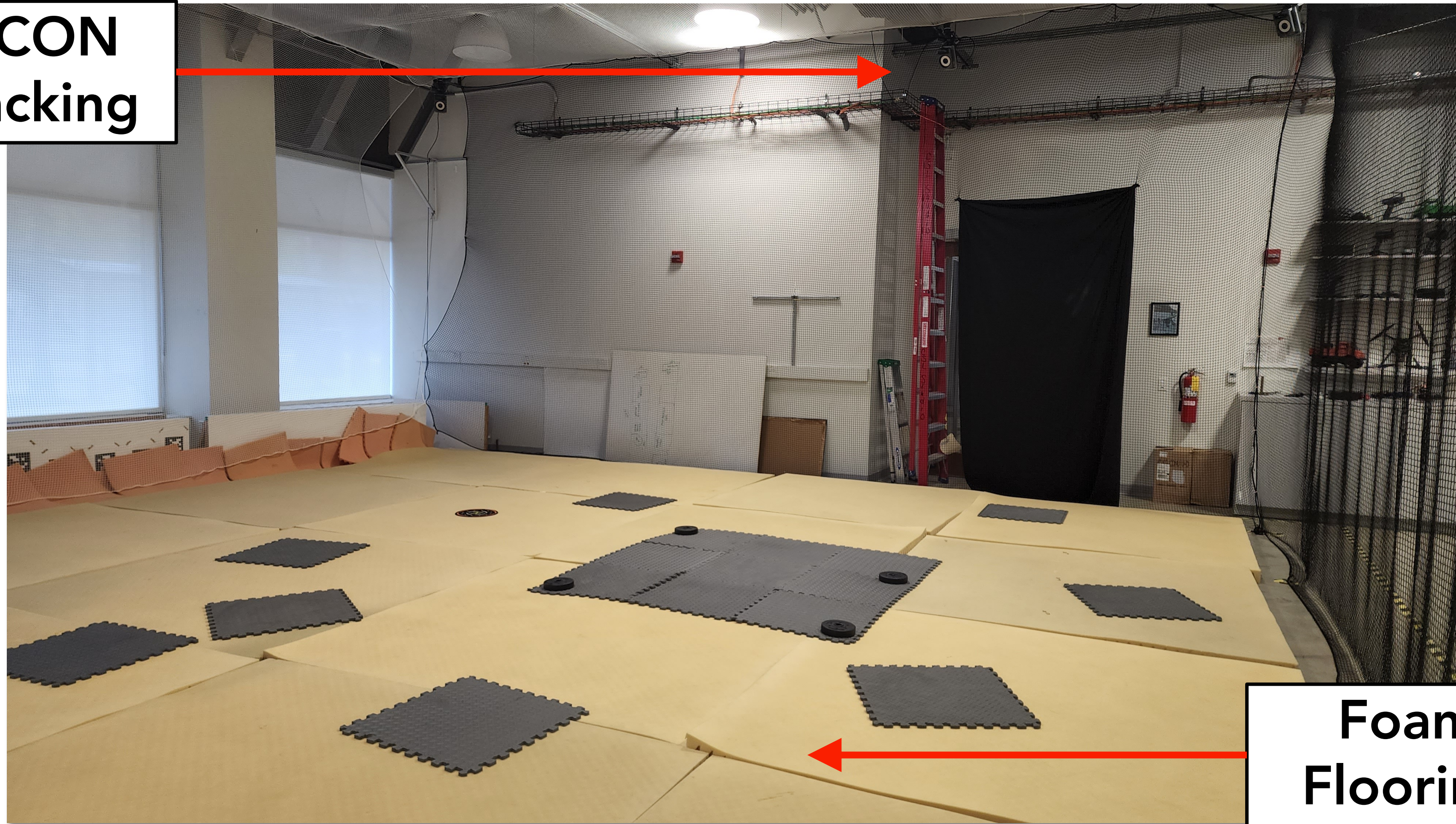

Overhead Radar
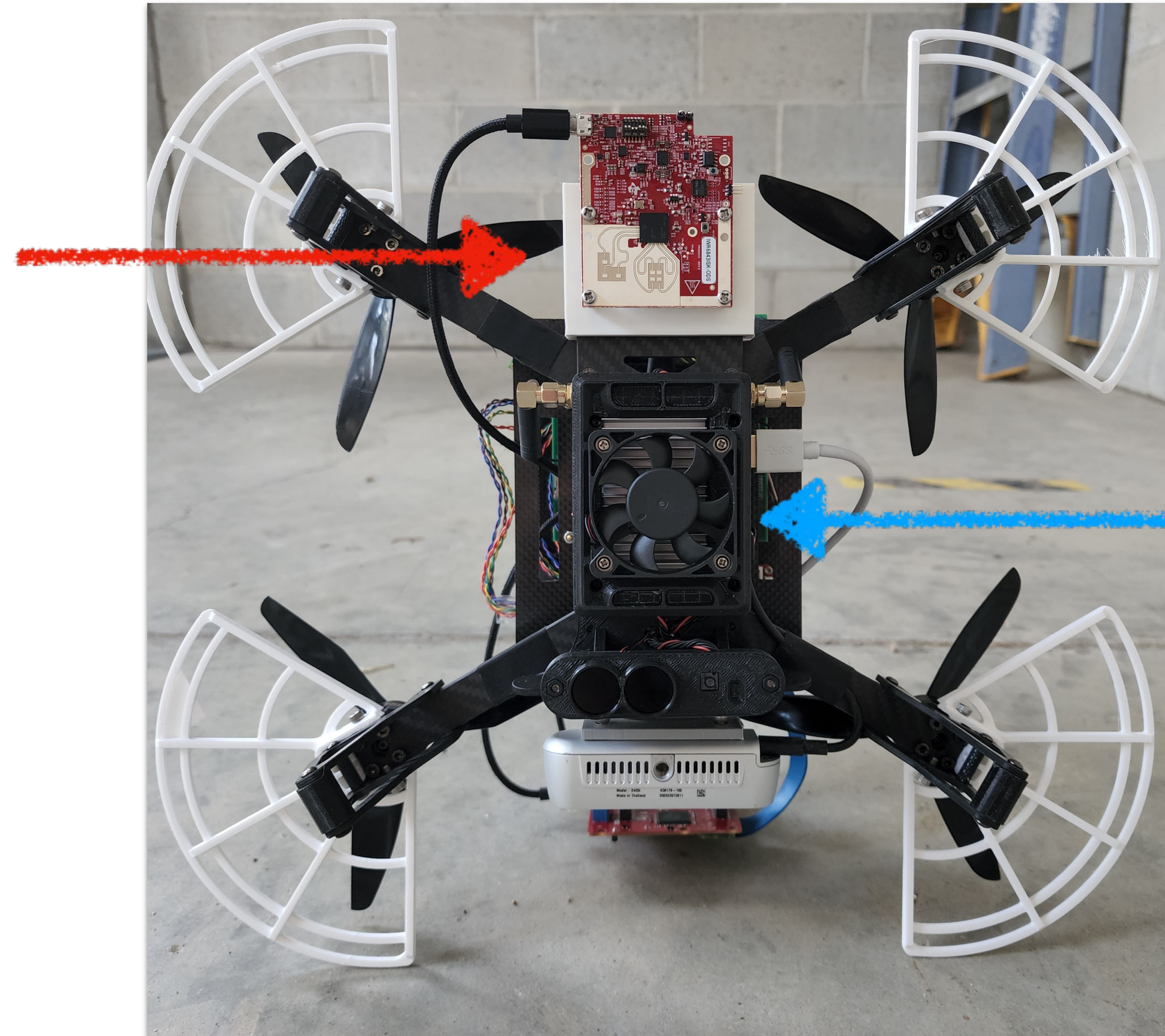
Intel Up Board

- Intel Atom x5-Z8350 (QuadCore 1.44Ghz)

- 4 GB RAM

Runs up to 40Hz on on-board CPU core
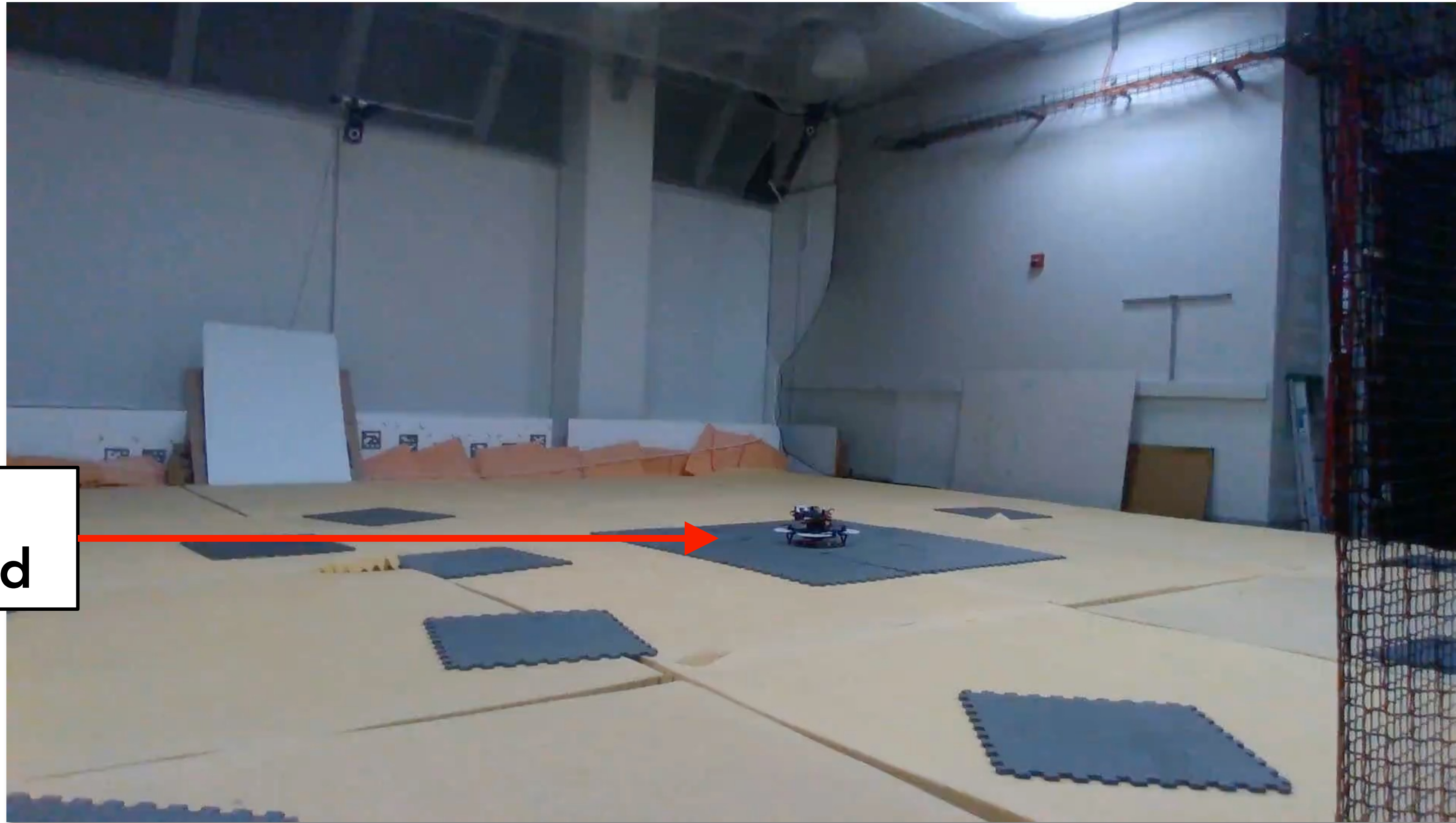
Hover Test

VICON Tracking

Foam Flooring

Fly drone to fixed height, measure horizontal drift
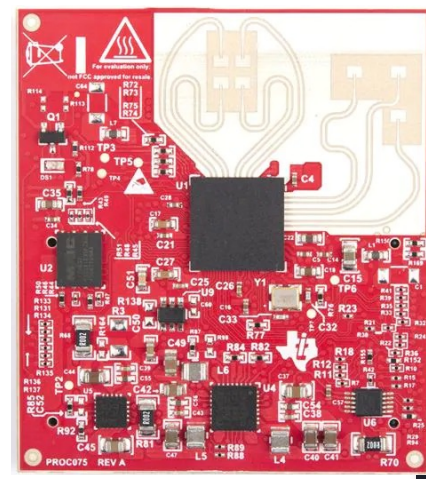
Optical Flow (Baseline)

Patterned
Landing Pad

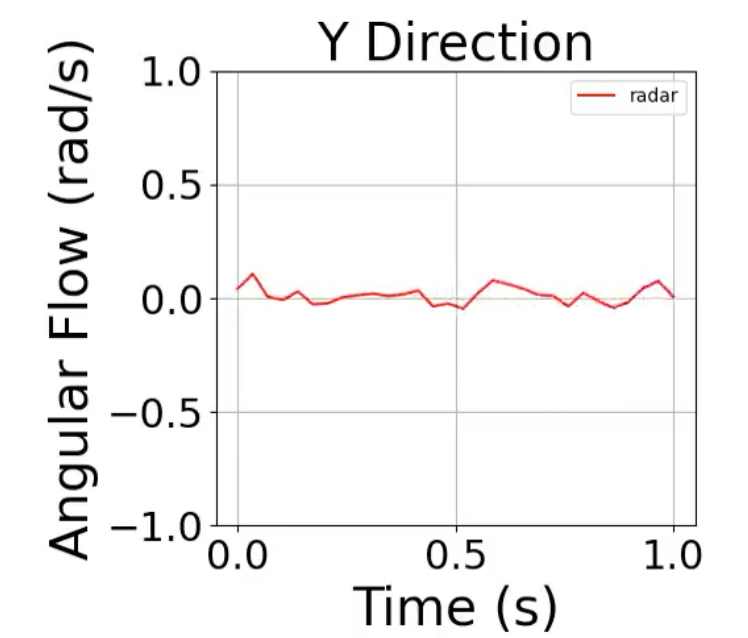# **Optical Flow** (Featureless)

Radio Flow (Featureless)

Optical Flow

Foam Floor
- **Looks smooth to radar**
- **Not in training set**

Optical Flow (Dark)
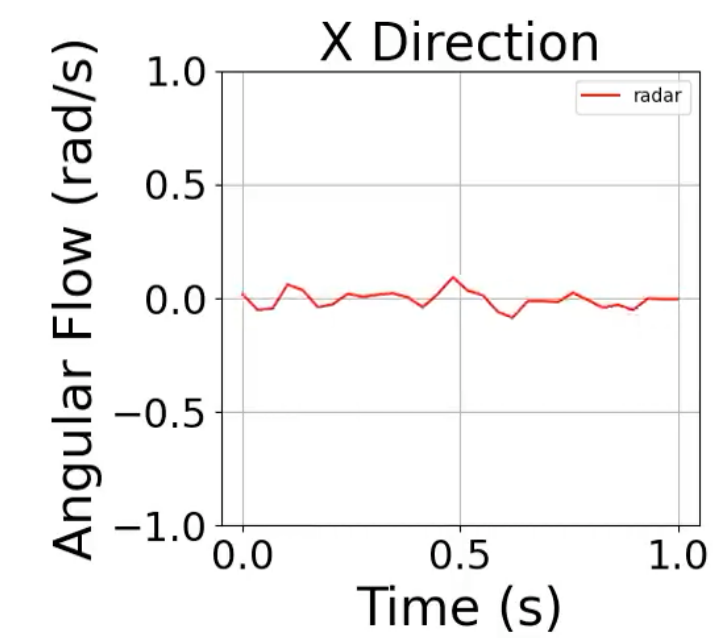
Patterned Landing Pad

Radio Flow (Dark)

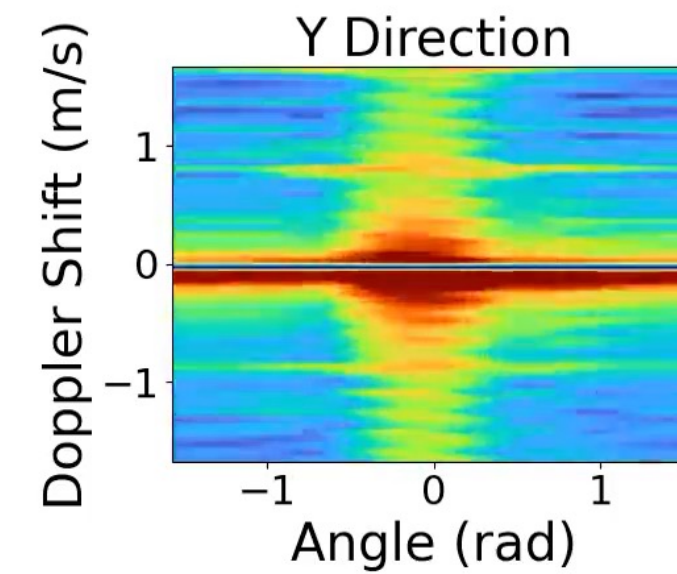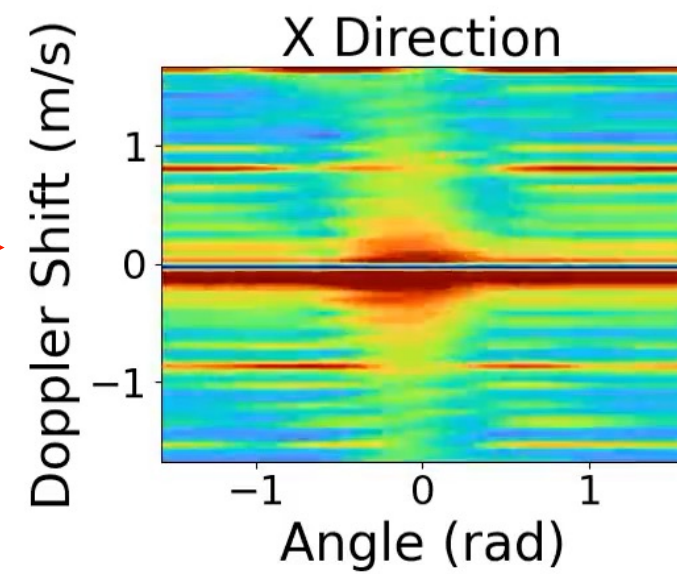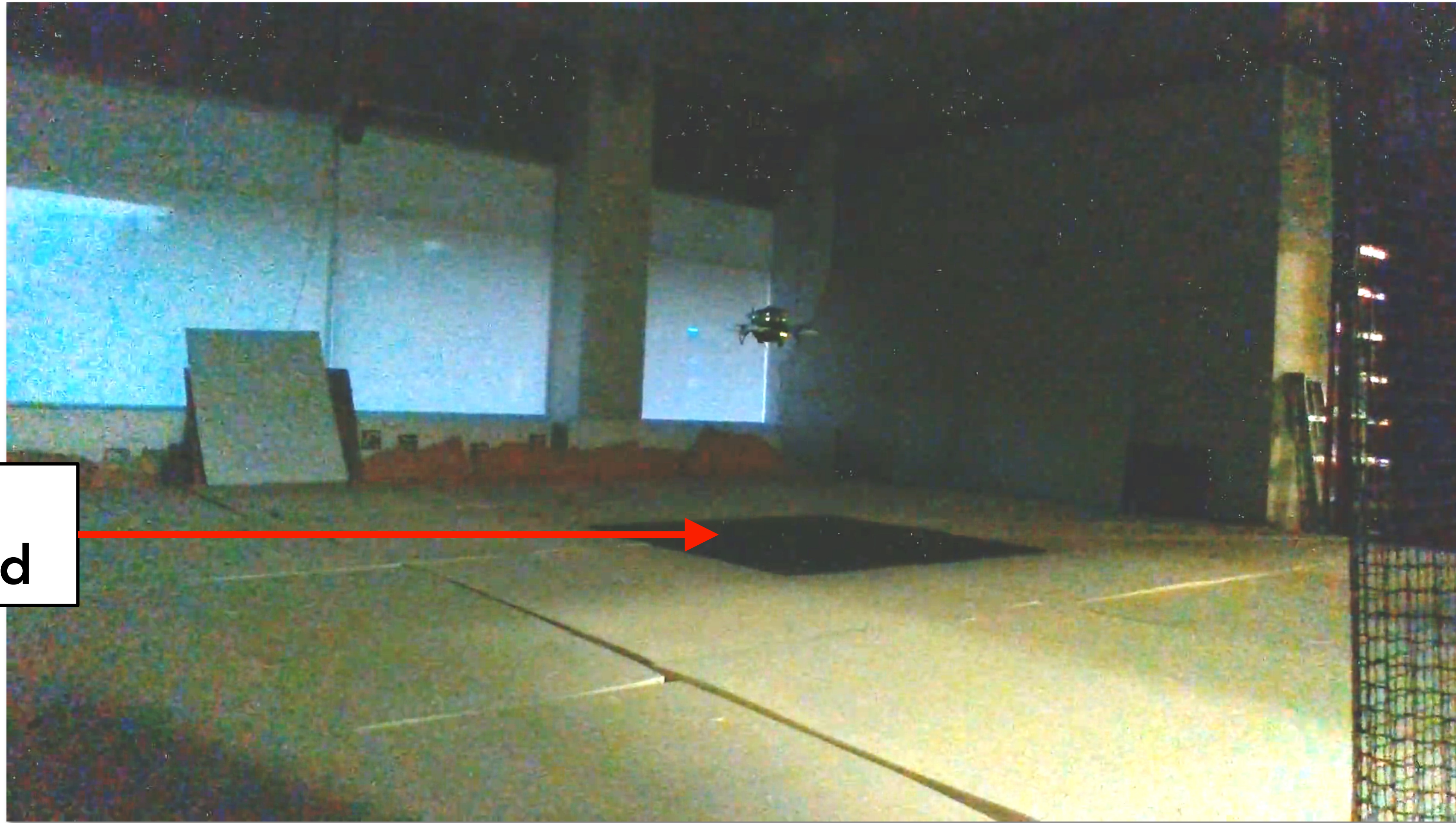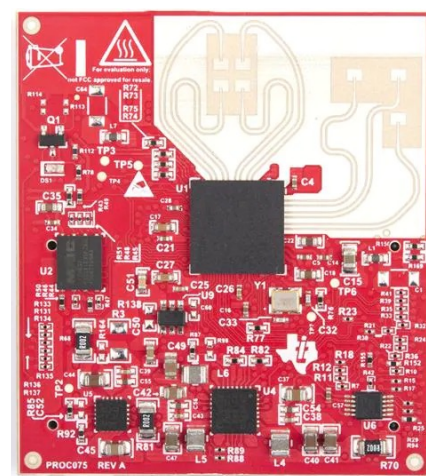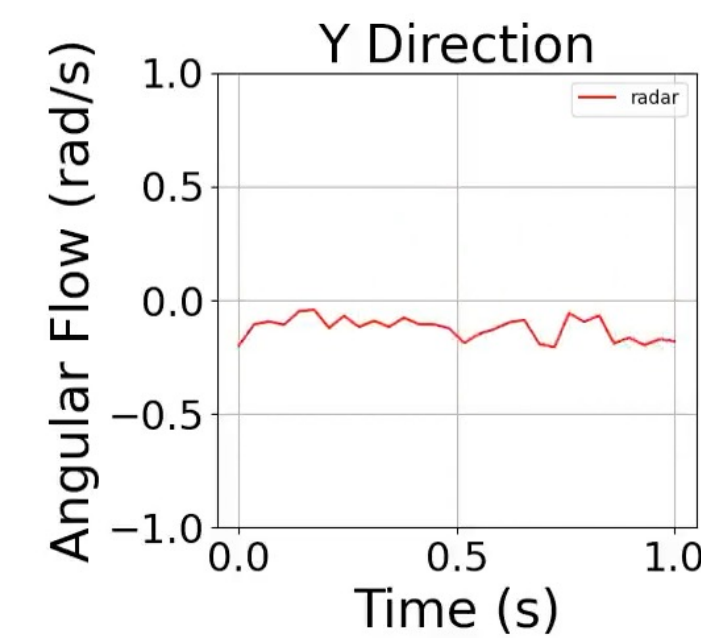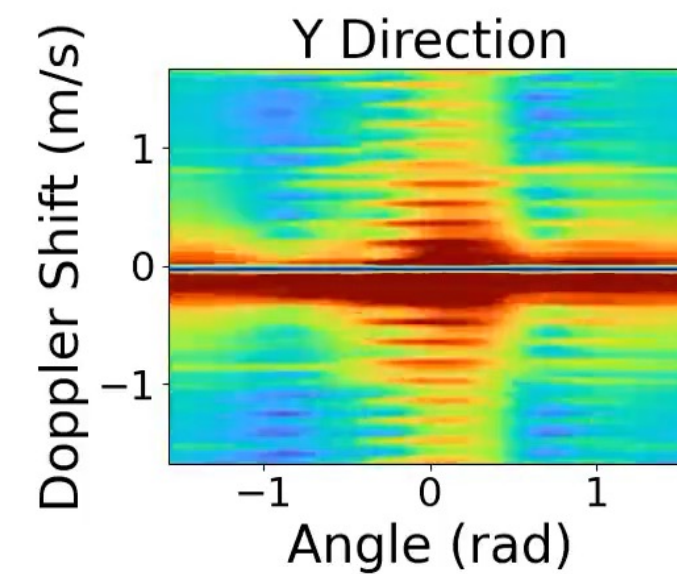**Optical Flow**

Foam Floor
- Looks smooth to radar
- Not in training set
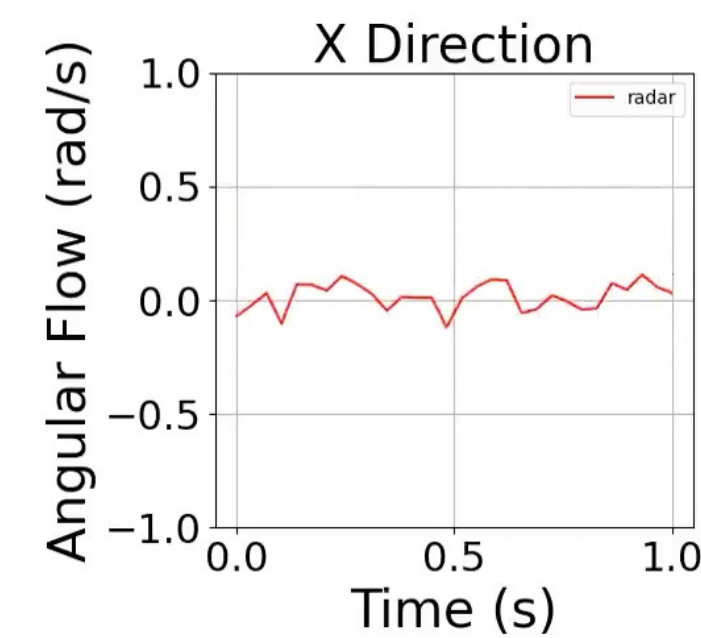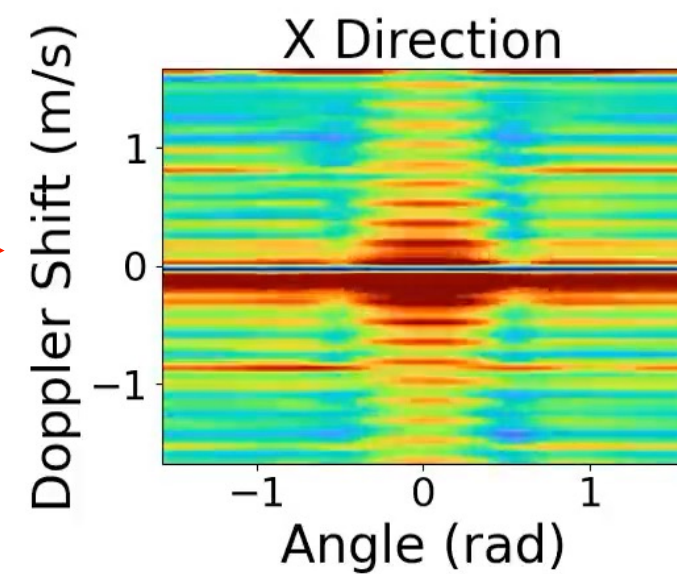
How does radio flow stack up?

Mean Deviation (m)

7 cm	Optical Flow
17 cm	Radio Flow
1.13 m	Optical Flow (Dark)
4.59 m	Optical Flow (Featureless)
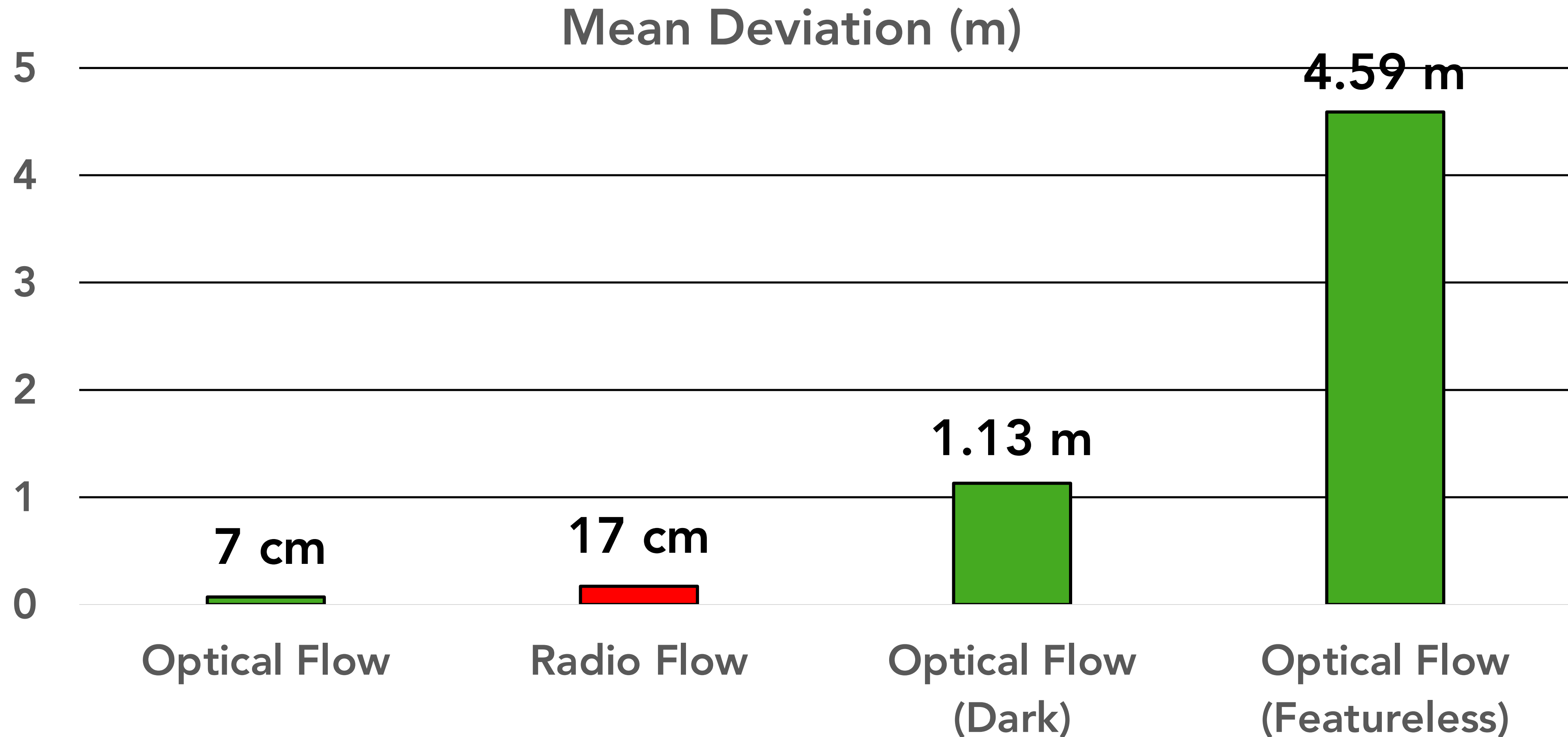
BatMobility Overview
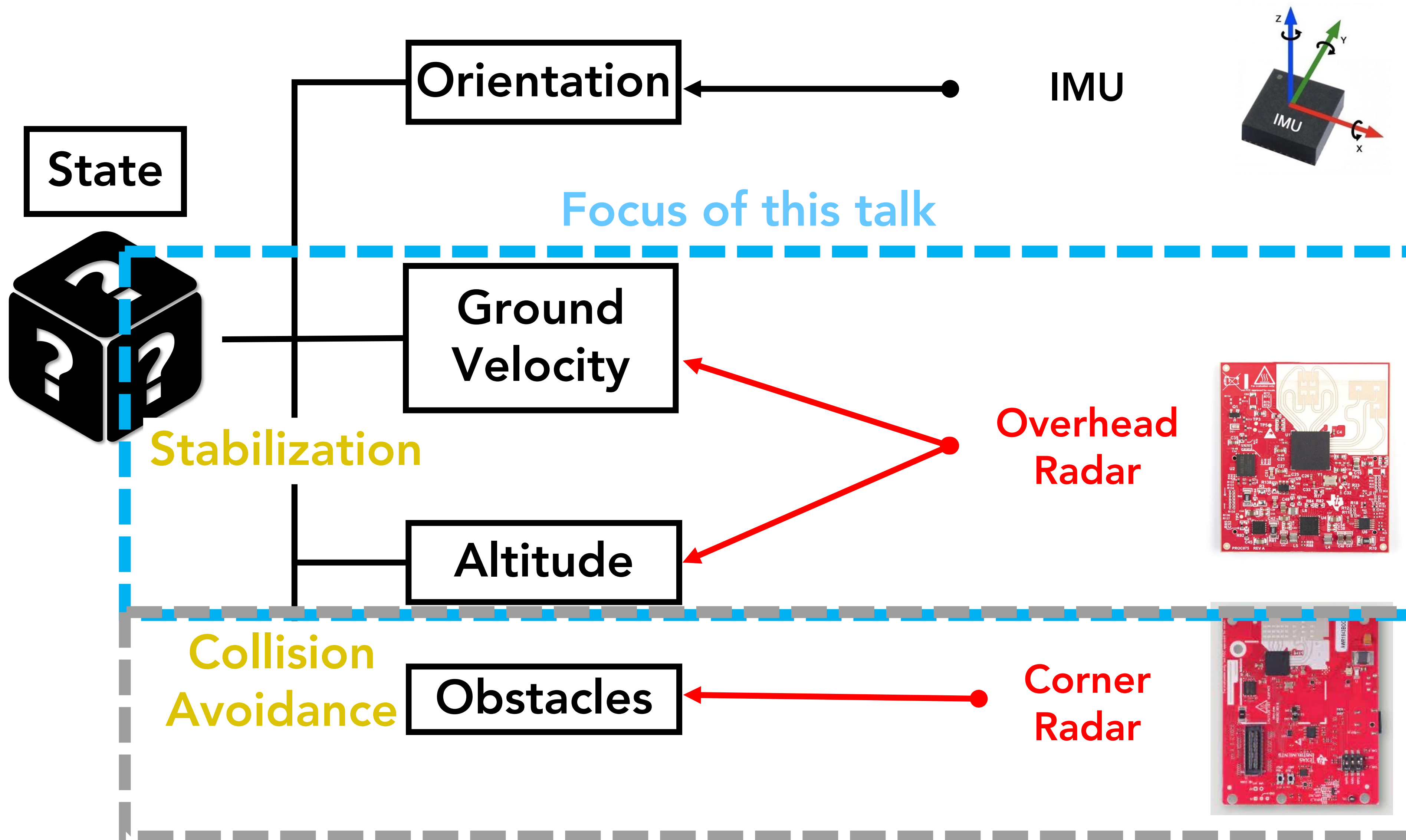
More demos, code, data available at project website

- We identify the phenomenon of *surface-parallel doppler shift* at mmWave frequencies.

- We introduce *radio flow* which is more robust than optical flow.

- We demonstrate radio flow as a *plug-and-play module* on an off-the-shelf drone.