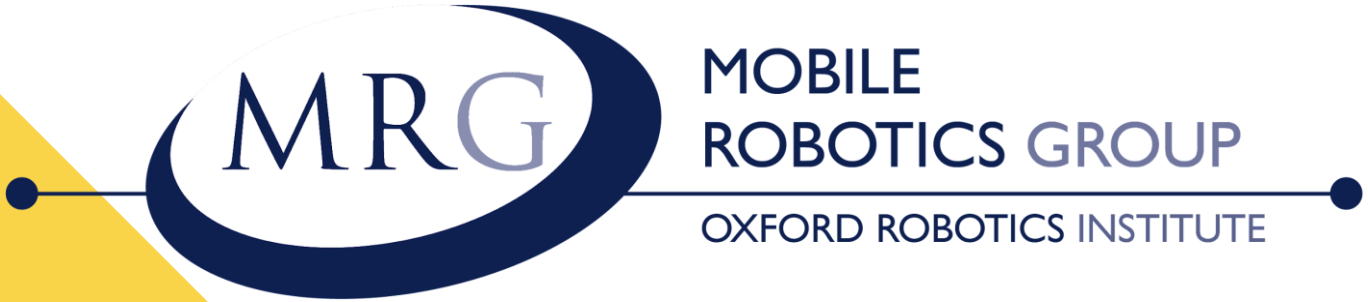
# FMCW radar, what's next? From off-road to Doppler

Daniele De Martini

# Who am I?

I co-lead with Professor Paul Newman the Mobile Robotics Group working on **robust navigation and scene understanding in challenging weather and scenarios,** by utilising inherently more robust sensors or enhancing the training of perception modules.

# More importantly, here is the radar!

Navtech CTS350-X Millimetre-Wave FMCW radar:

- 4 Hz, 400 measurements per rotation
- 2◦ beamwidth
- Resolution:
  - 4.5 cm -> 160 m range or
  - 16.5 cm -> 600 m range





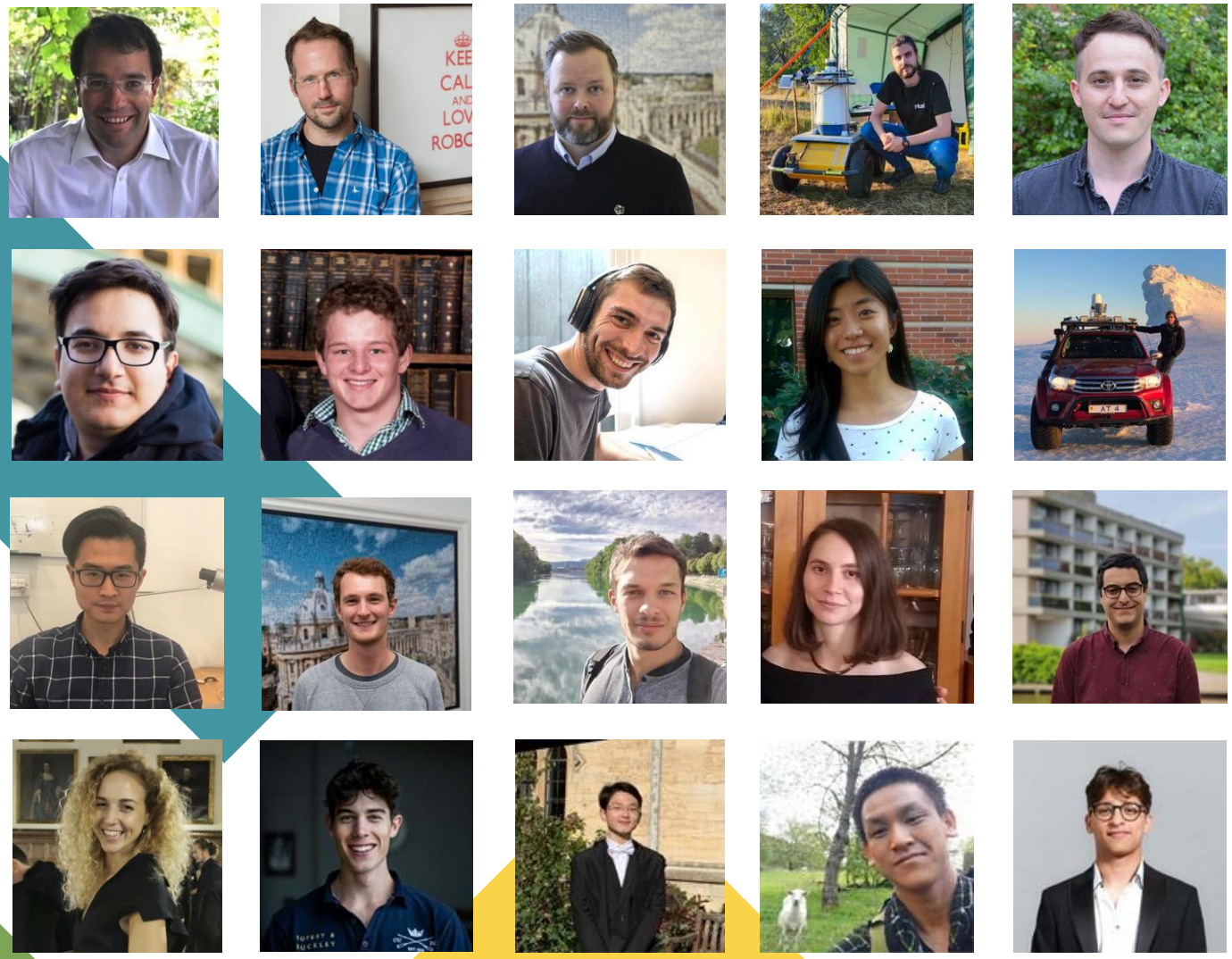







MRG

MOBILE
ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE



MRG

MOBILE ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE

COGNITIVE ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE

A²I

APPLIED ARTIFICIAL INTELLIGENCE LAB
OXFORD ROBOTICS INSTITUTE

MRG

MOBILE ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE

COGNITIVE ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE

A²I

APPLIED ARTIFICIAL INTELLIGENCE LAB
OXFORD ROBOTICS INSTITUTE

# What are we covering today?

## History and background

MRG’s research in radar

## We want radar data!

What is out there and what is missing

## Can radar evolve?

Can increased functionalities help?

## Some final thoughts

Leading towards the final discussion panel

# History and background

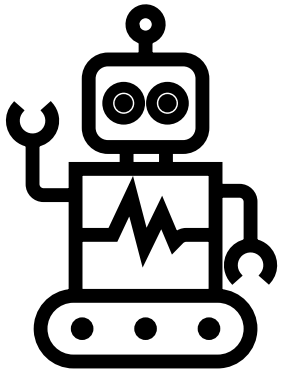
MRG’s research in radar

# The three questions

Where am I?

What surrounds me?

What should I do next?



# The three questions

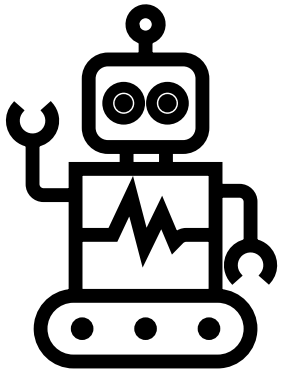
Odometry

Localisation

Object detection

Segmentation

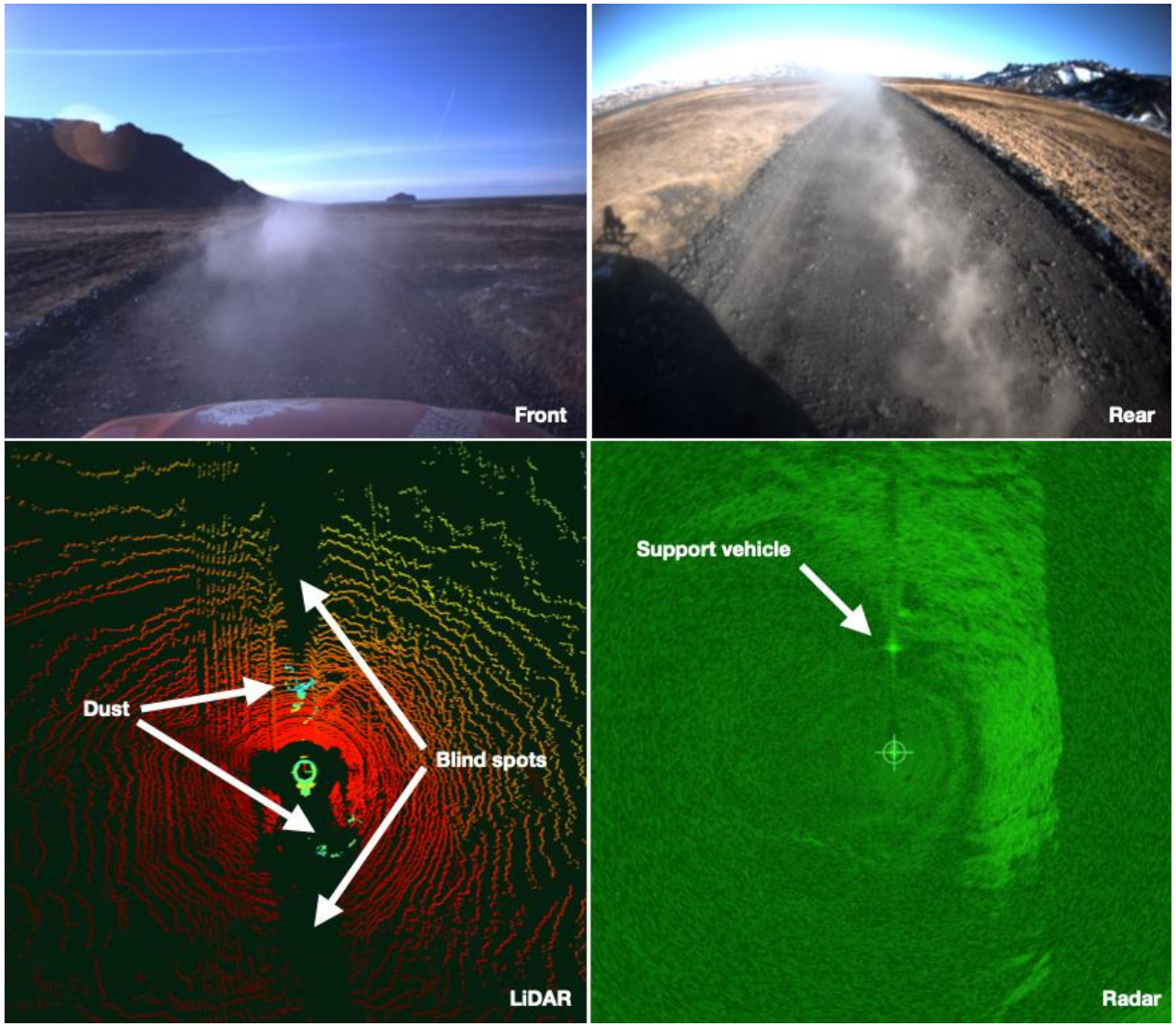
Planning




ROBOTCAR

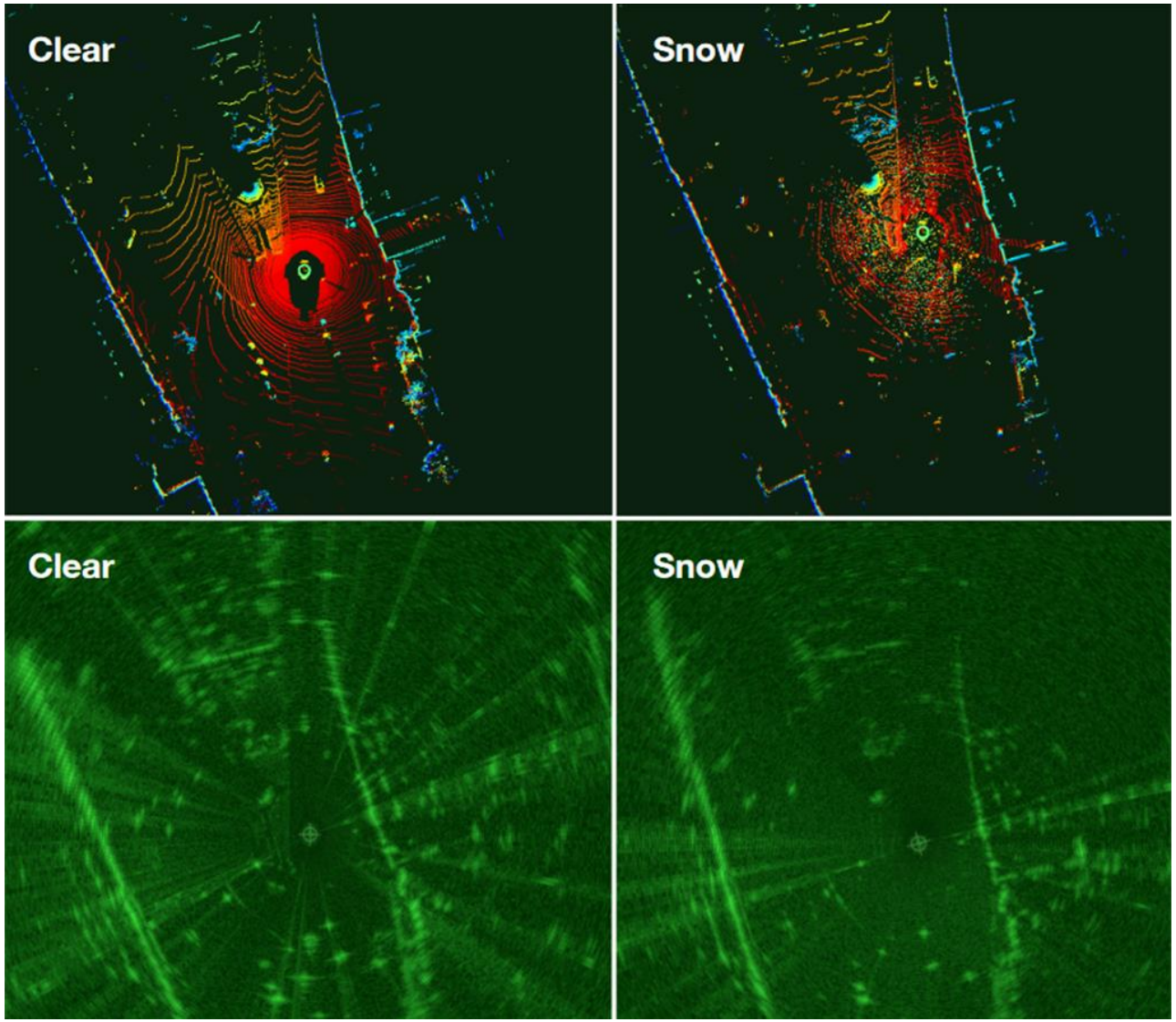
# Radar vs dust

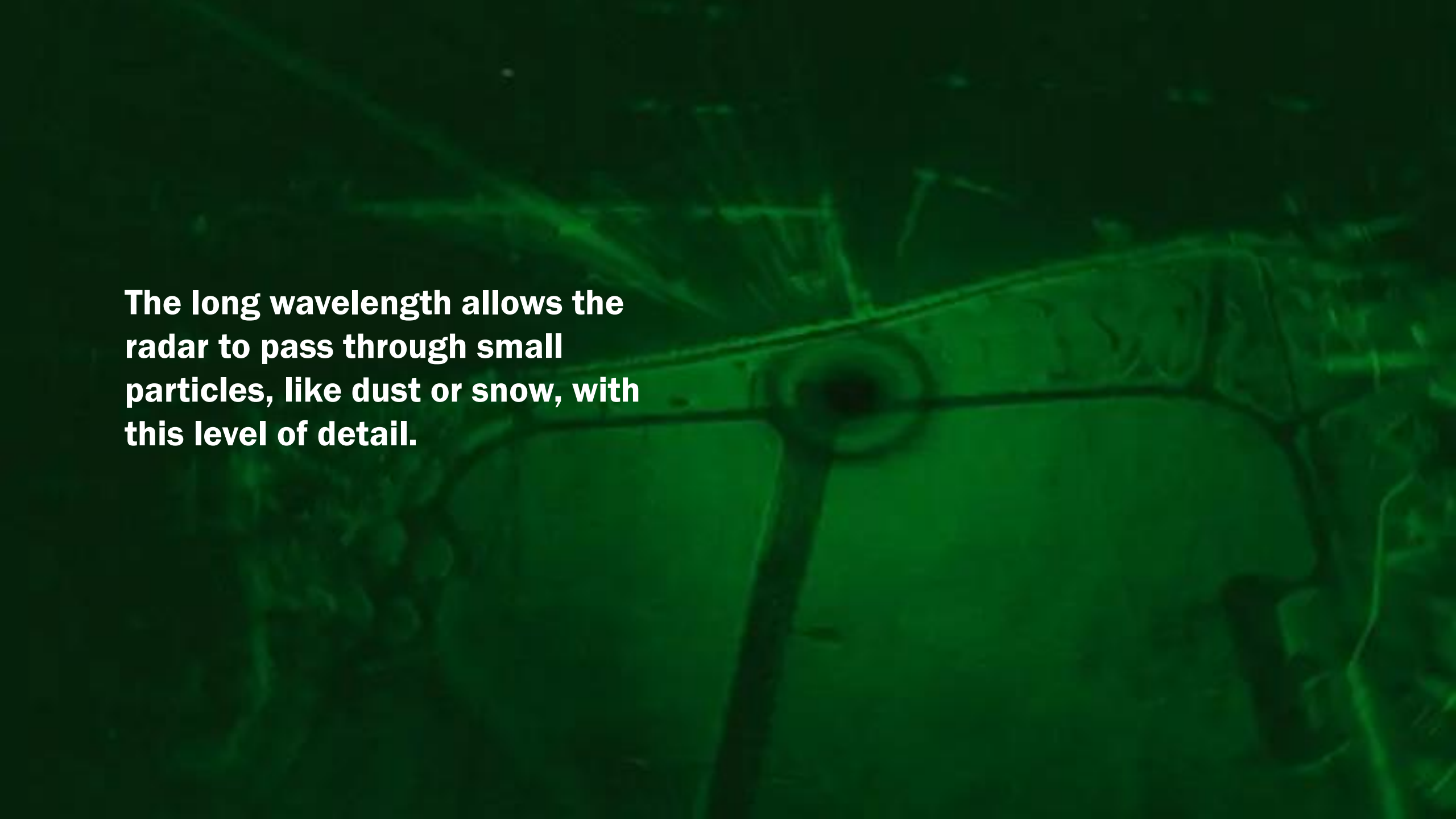
The long wavelength allows the radar to pass through small particles, like dust…



# Radar vs snow

The long wavelength allows the radar to pass through small particles, like dust or snow…





The long wavelength allows the radar to pass through small particles, like dust or snow, with this level of detail.




# The Platforms



# The Platforms


# Timeline of MRG's radar projects

**2018**
- FMCW radar odometry

**2019**
- Radar deep segmentation (stable features)
- Radar place recognition
- More robust FMCW radar odometry
- Urban FMCW radar dataset

**2020**
- Radar full semantic segmentation
- Radar-only metric localisation
- Radar-satellite topological localisation
- Radar-only drivable terrain assessment
- Radar-only route proposal

**2021**
- Radar-satellite metric localisation
- Self-supervised radar-satellite metric localisation
- Unsupervised radar-only topological localisation

**2022**
- Improved robustness of radar-odometry estimation
- "Real-time" embedded radar-odometry

**2023**
- Doppler-aware FMCW scanning radar odometry
- Inclusion of uncertainty in radar localisation

**2024**
- Off-road radar dataset (Scotland)
- Public place recognition benchmark
- [In preparation] SAX dataset

# Timeline of MRG's radar projects

- Odometry
- Localisation
- Sensor fusion / crossmodal
- Segmentation
- Planning
- Dataset

**2018**
- FMCW radar odometry

**2019**
- Radar deep segmentation (stable features)
- Radar place recognition
- More robust FMCW radar odometry
- Urban FMCW radar dataset

**2020**
- Radar full semantic segmentation
- Radar-only metric localisation
- Radar-satellite topological localisation
- Radar-only drivable terrain assessment
- Radar-only route proposal

**2021**
- Radar-satellite metric localisation
- Self-supervised radar-satellite metric localisation
- Unsupervised radar-only topological localisation

**2022**
- Improved robustness of radar-odometry estimation
- "Real-time" embedded radar-odometry

**2023**
- Doppler-aware FMCW scanning radar odometry
- Inclusion of uncertainty in radar localisation

**2024**
- Off-road radar dataset (Scotland)
- Public place recognition benchmark
- [In preparation] SAX dataset

# Timeline of MRG's radar projects

- Urban
- Rural
- Off-road

**2018**
- FMCW radar odometry

**2019**
- Radar deep segmentation (stable features)
- Radar place recognition
- More robust FMCW radar odometry
- Urban FMCW radar dataset

**2020**
- Radar full semantic segmentation
- Radar-only metric localisation
- Radar-satellite topological localisation
- Radar-only drivable terrain assessment
- Radar-only route proposal

**2021**
- Radar-satellite metric localisation
- Self-supervised radar-satellite metric localisation
- Unsupervised radar-only topological localisation

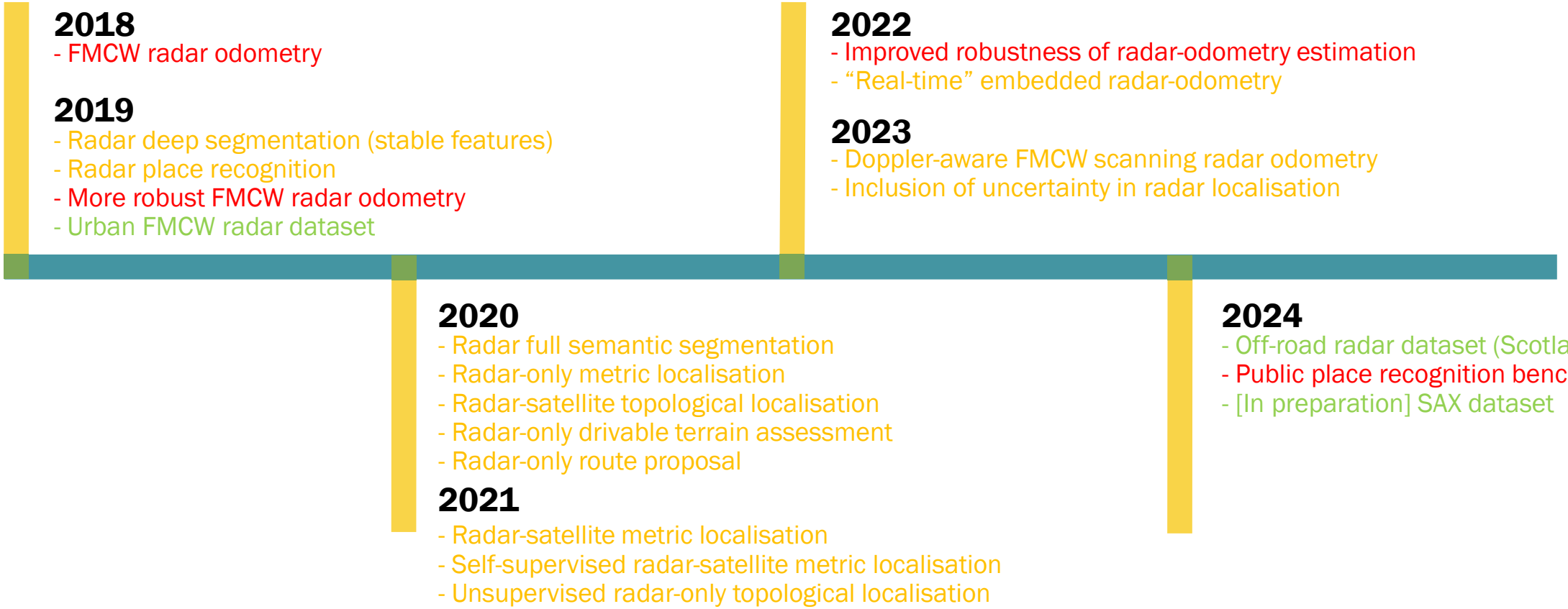
**2022**
- Improved robustness of radar-odometry estimation
- "Real-time" embedded radar-odometry

**2023**
- Doppler-aware FMCW scanning radar odometry
- Inclusion of uncertainty in radar localisation

**2024**
- Off-road radar dataset (Scotland)
- Public place recognition benchmark
- [In preparation] SAX dataset

# Timeline of MRG's radar projects

- Classic approach
- Deep Learning approach
- Dataset



# We want radar data!

What is out there and what is missing

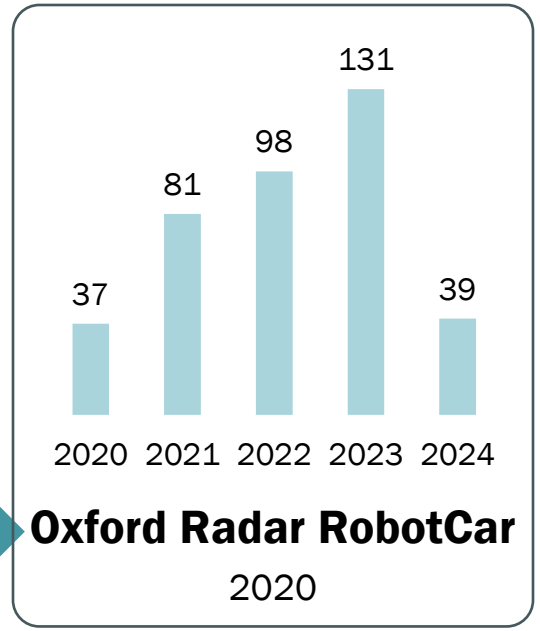
# Popular FMCW datasets

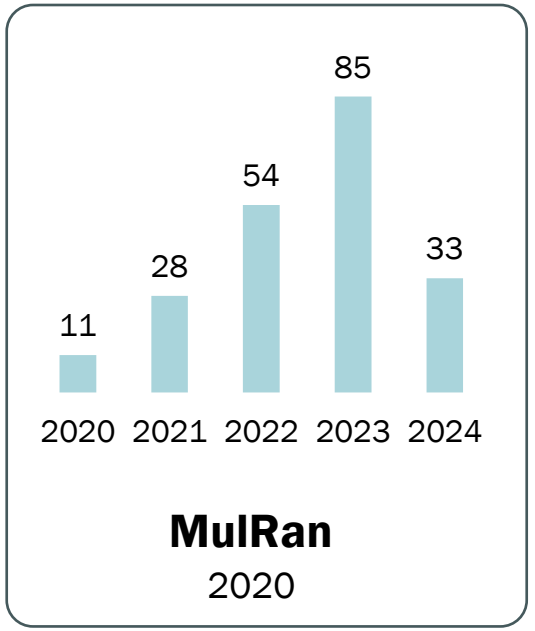
| Dataset | Year | Ground truths |
|---|---|---|
| Oxford Radar RobotCar | 2020 | Odometry/localisation |
| MulRan | 2020 | Odometry/localisation |
| Radiate | 2021 | Object detection |
| Boreas | 2022 | Object detection/ odometry/localisatoin |

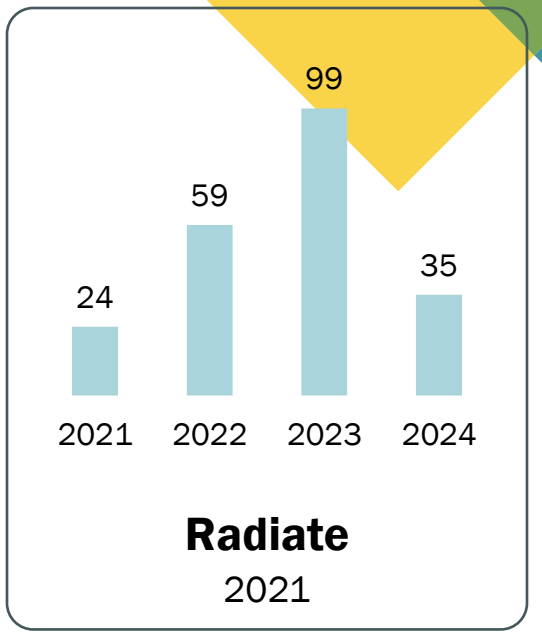
# Popular FMCW datasets

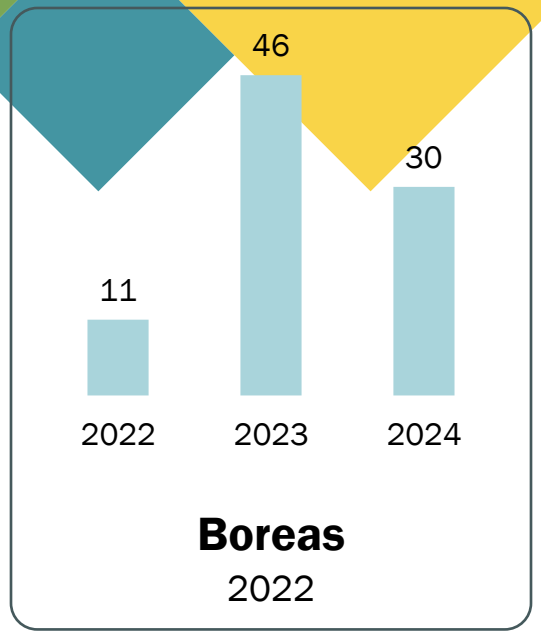
| Dataset | Year | Length |
|---|---|---|
| Oxford Radar RobotCar | 2020 | 280 km |
| MulRan | 2020 | 125 km |
| Radiate | 2021 | 3 h (150-200 km?) |
| Boreas | 2022 | 350 km |

# Popular FMCW datasets



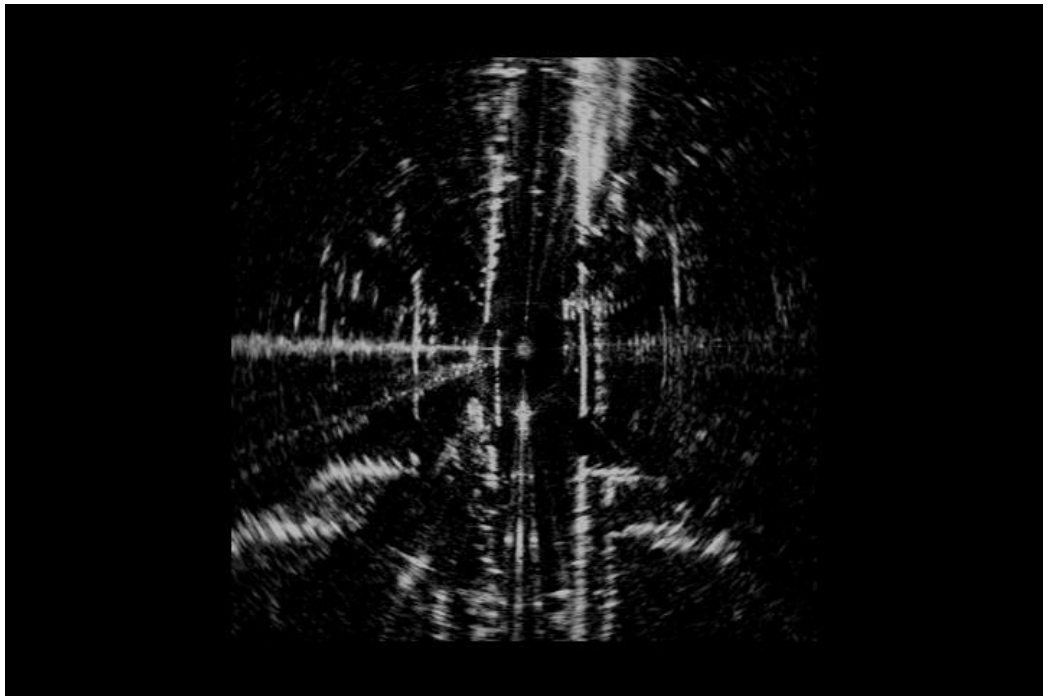
# What do they look like?

Radar Robotcar

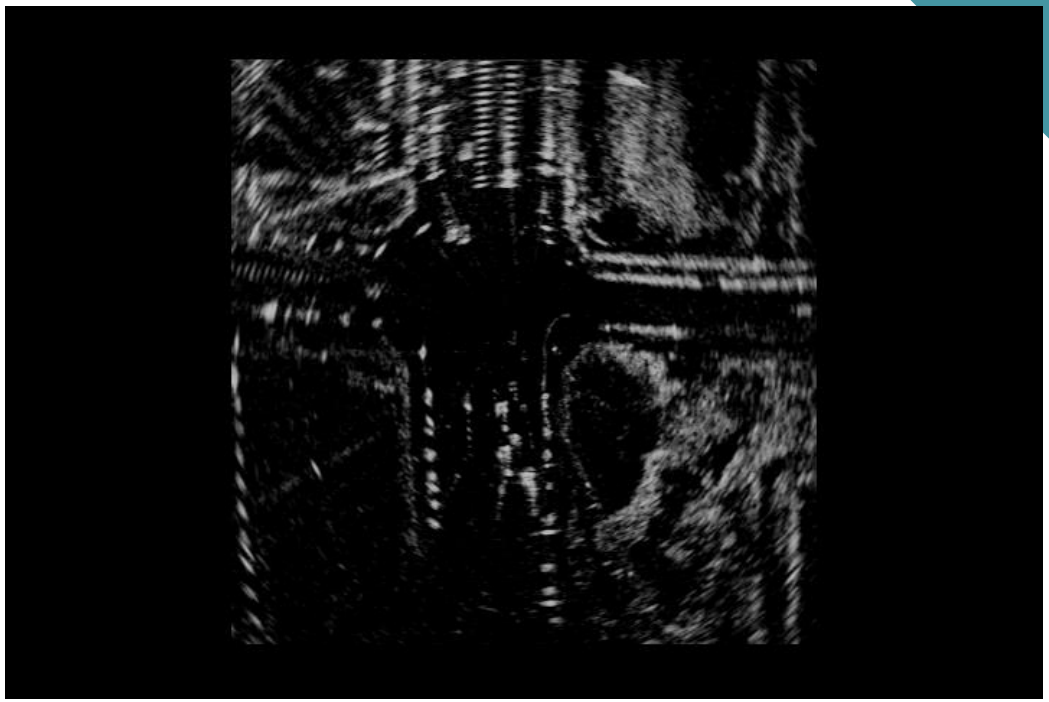
Mulran

# What do they look like?

Radar Robotcar



Mulran



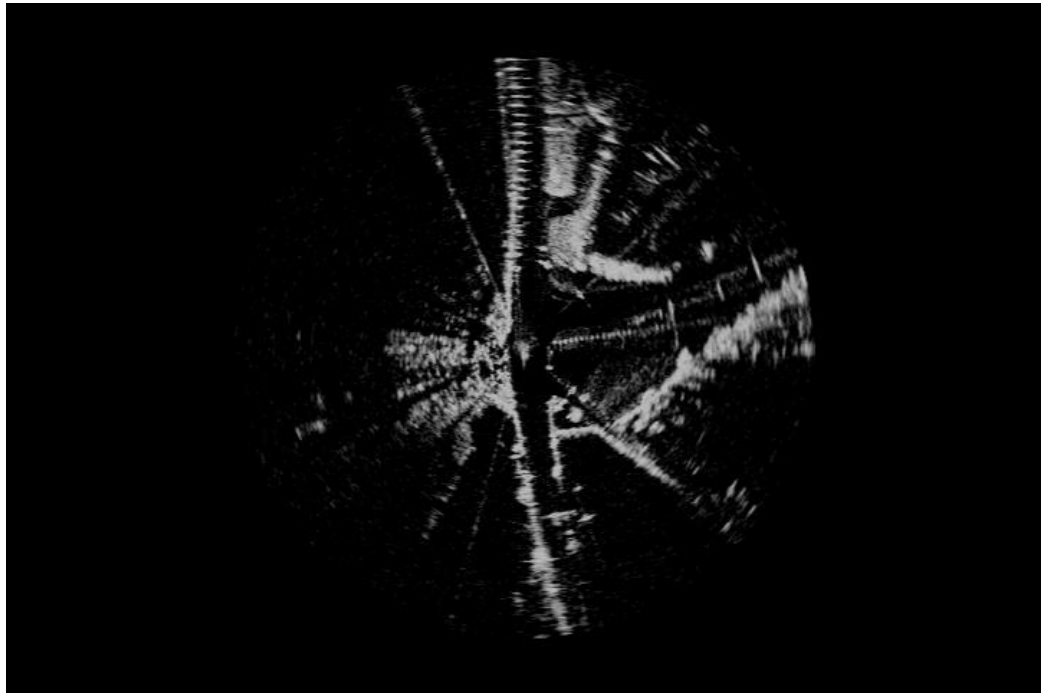
# What do they look like?

Radiate

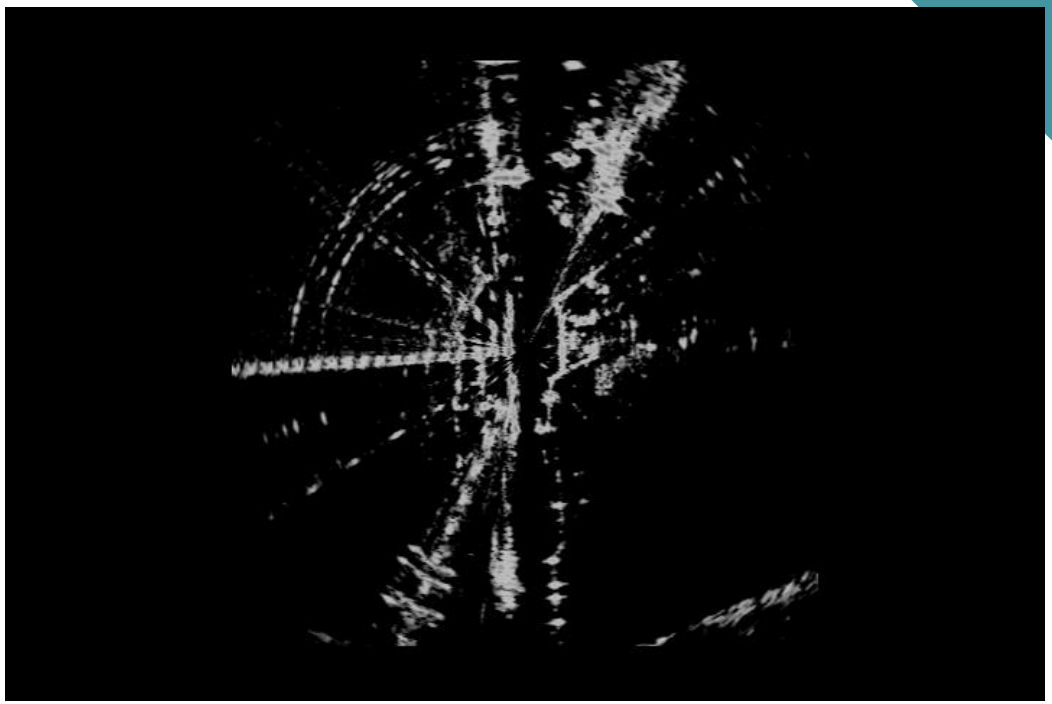
Boreas

# What do they look like?

Radiate



Boreas

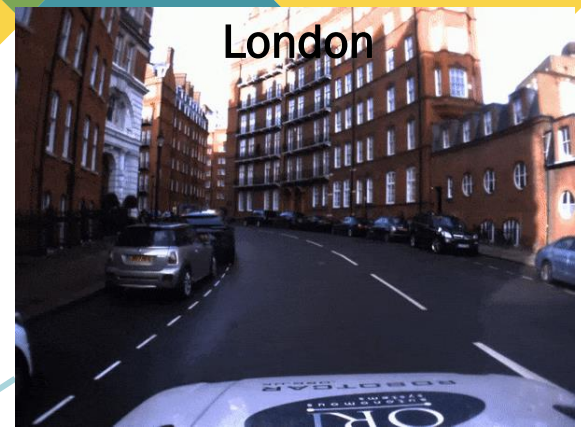


“

Are we not missing a huge slice of the possible applications radar can be most beneficial to?

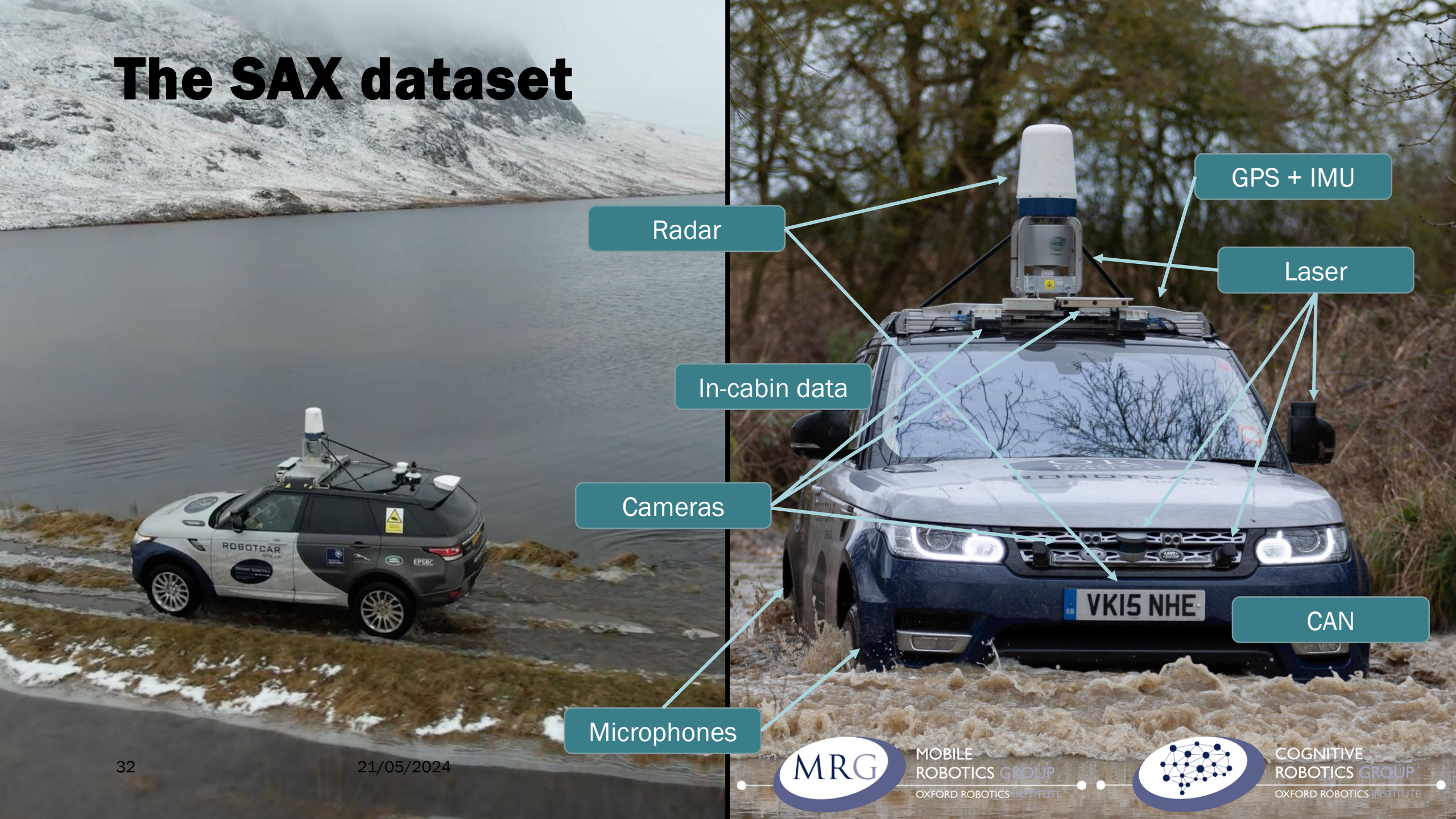
# The SAX dataset







# The SAX dataset



# Popular FMCW datasets

| Dataset | Year | Length |
|---|---|---|
| Oxford Radar RobotCar | 2020 | 280 km |
| MulRan | 2020 | 125 km |
| Radiate | 2021 | 3 h (150-200 km?) |
| Boreas | 2022 | 350 km |
| SAX | 2024 | ~3500 km |

# Urban data

# Rural data

# Off-road data

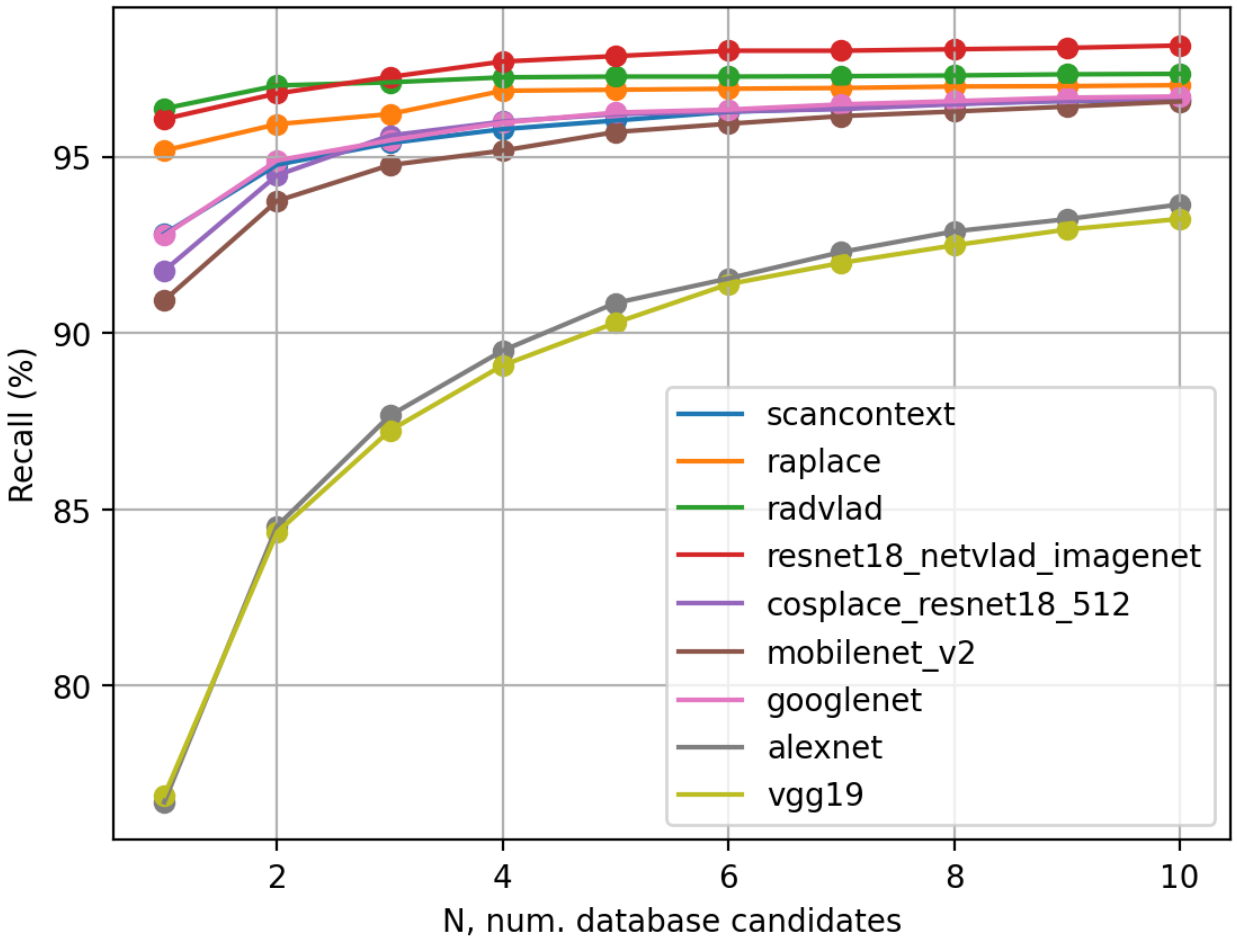
# Off-road data (even worse)

# The Oxford Offroad Radar Dataset (OORD)

# Off-road data (radar)

# Preliminary results: localisation

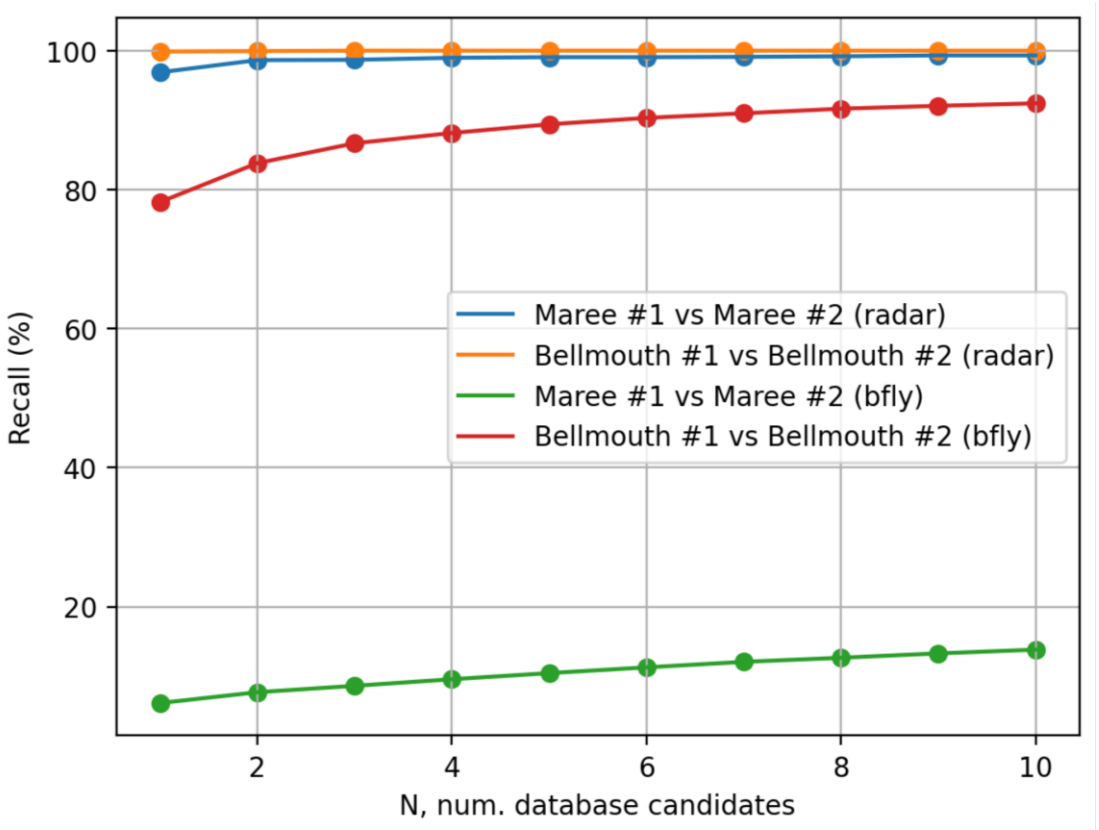
We showed how radar localisation pipelines perform on this **out-of-distribution** data.



# Preliminary results: localisation

We showed how radar localisation pipelines perform on this **out-of-distribution** data.

And with early results we **might** do better than cameras.




Bellmouth

Maree

# Something tells me we are not alone

"*FoMo: A Proposal for a Multi-Season Dataset for Robot Navigation in Forêt Montmorency*" by M. Boxan, A. Krawciw, E. Daum, X. Qiao, S. Lilge, T. Barfoot, F. Pomerleau

Presented at the Workshop on Field Robotics!

# Ground-truth signals

- Object detection (camera, lidar, radar)
- Instance segmentation (camera, lidar, radar)
- Leica position tracking
- Events
- Driving causes
- Vehicle controls (CAN)

# Ground-truth signals

- Object detection (camera, lidar, radar)
- Instance segmentation (camera, lidar, radar)
- Leica position tracking
- Events
- Driving causes
- Vehicle controls (CAN)

# Can radar evolve?

Can increased functionalities help?

# What do I intend for “evolution”?

## Completely new functionalities

Are there functionalities that are now missing and would benefit the community?

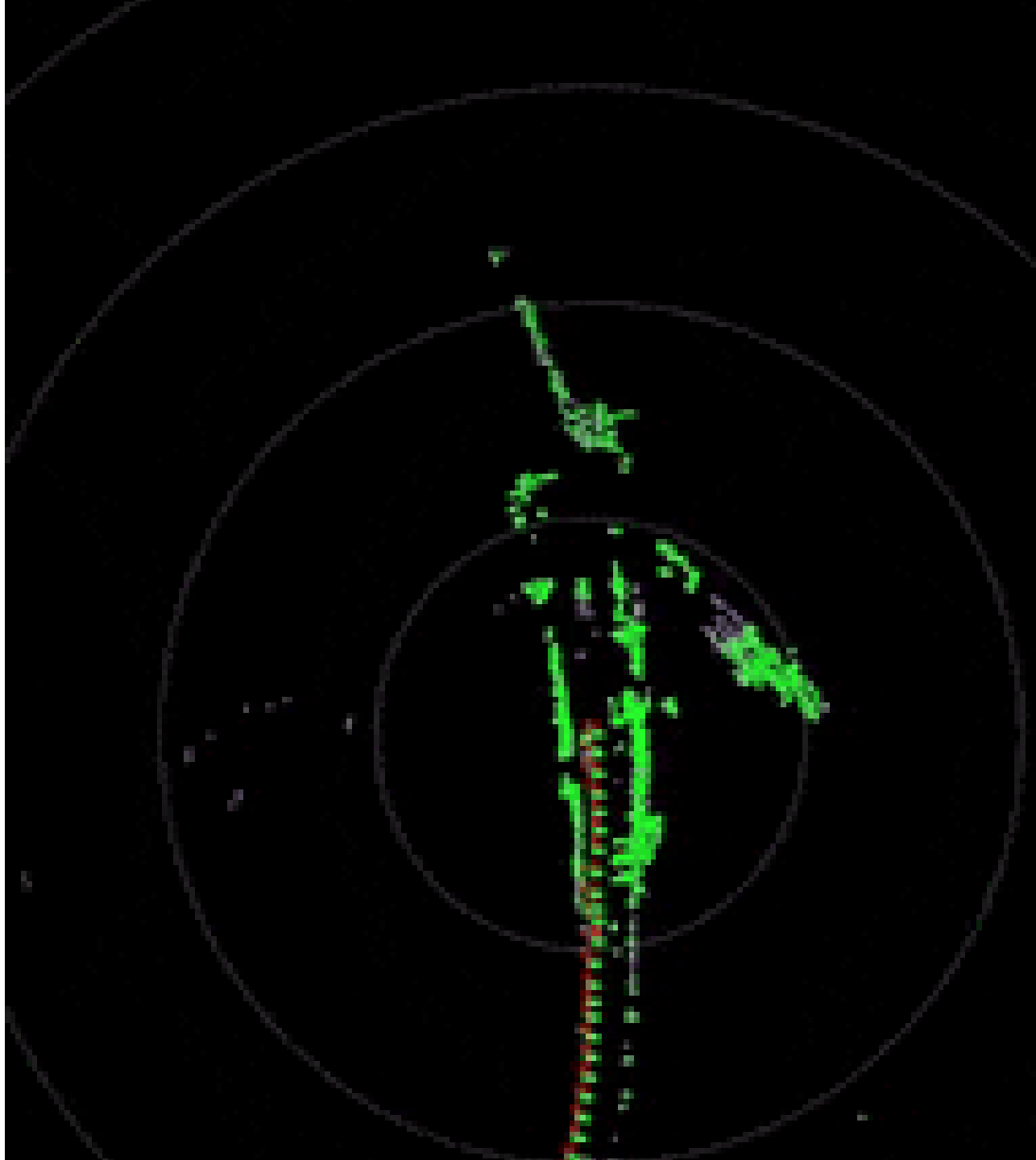
## Enhance existing functionalities to expand operations

What characteristics would benefit the community if enhanced?

# Am I moving or am I still?

When degenerate scenes are detected, we get degenerate solutions.

We tackled it with filtering, but now we can get additional signals



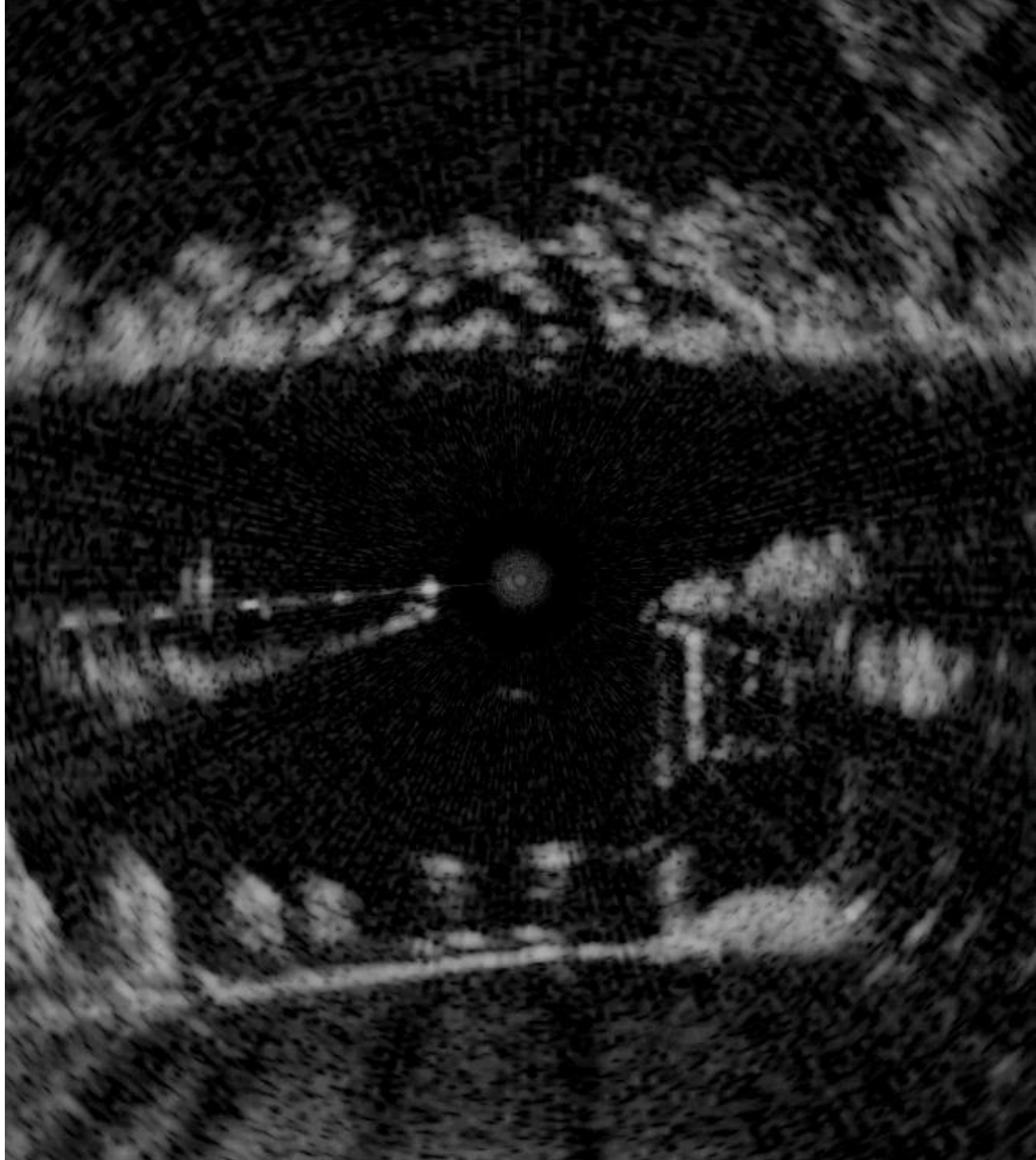
# What if we had more information?

What if FMCW radar can give us Doppler information as we know automotive radar does?

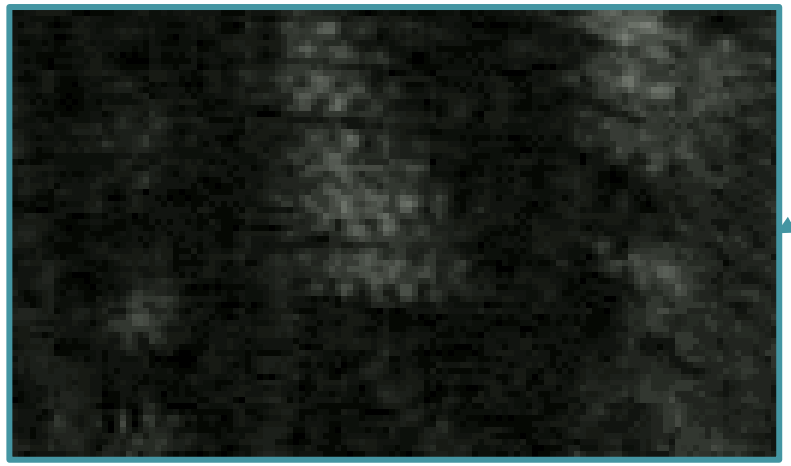
Collab with:

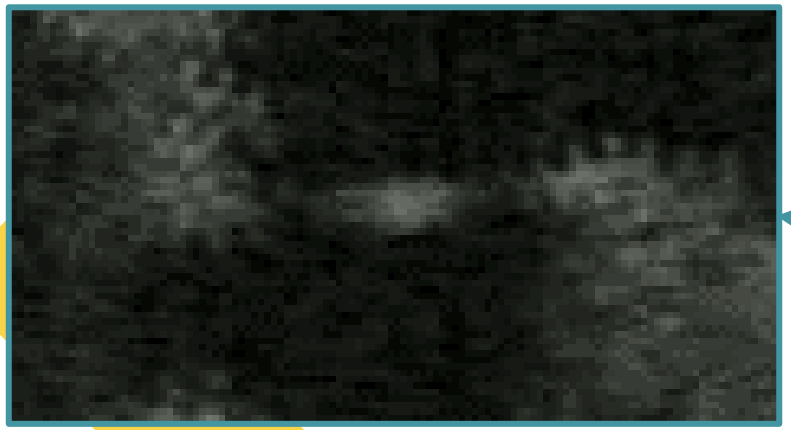
NAVTECH RADAR

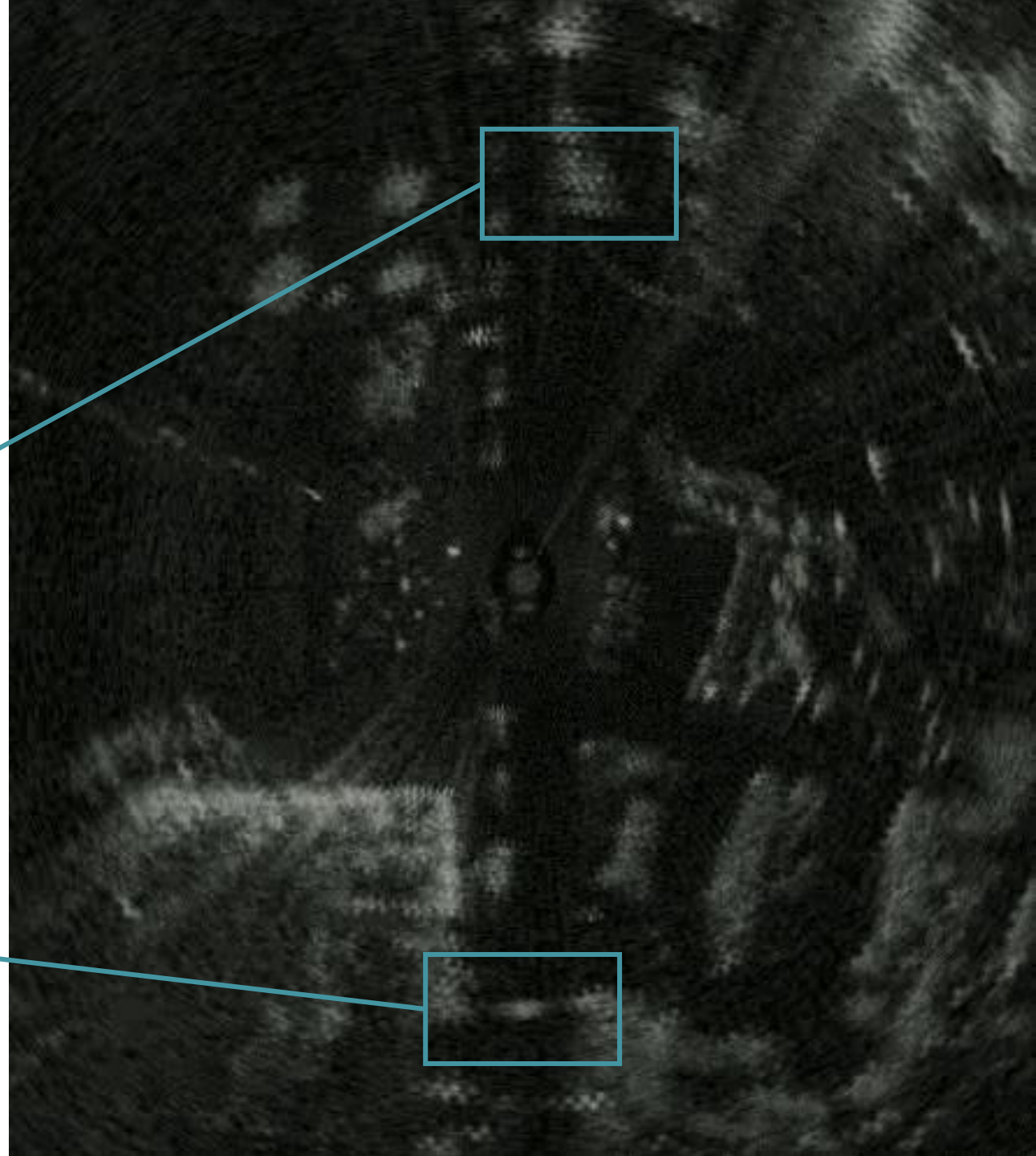
oxa Universal Autonomy



# Doppler radar

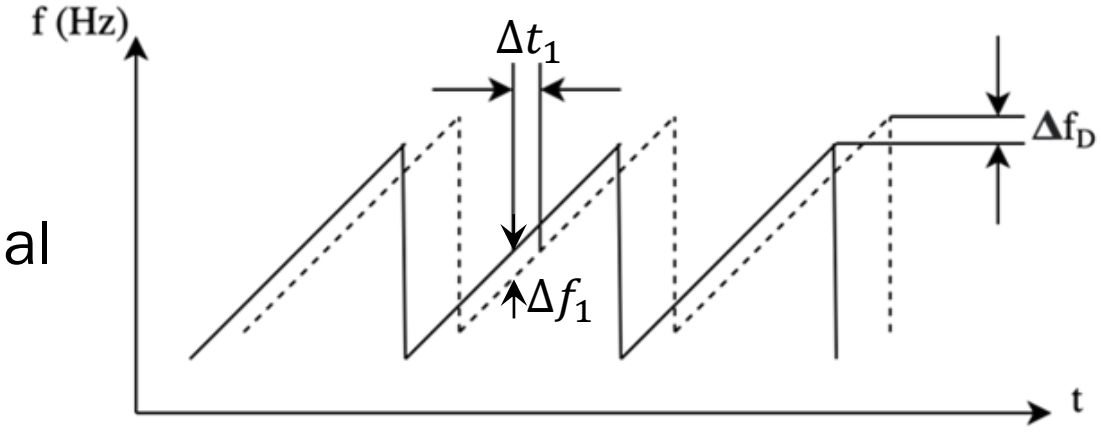






# What's the math behind it?

The distance of a detection $R$ is proportional to the ToF of the wave $\frac{\Delta t}{2}$, which can be calculated from the frequency shift wave $\Delta F$ and the slope of the modulation.

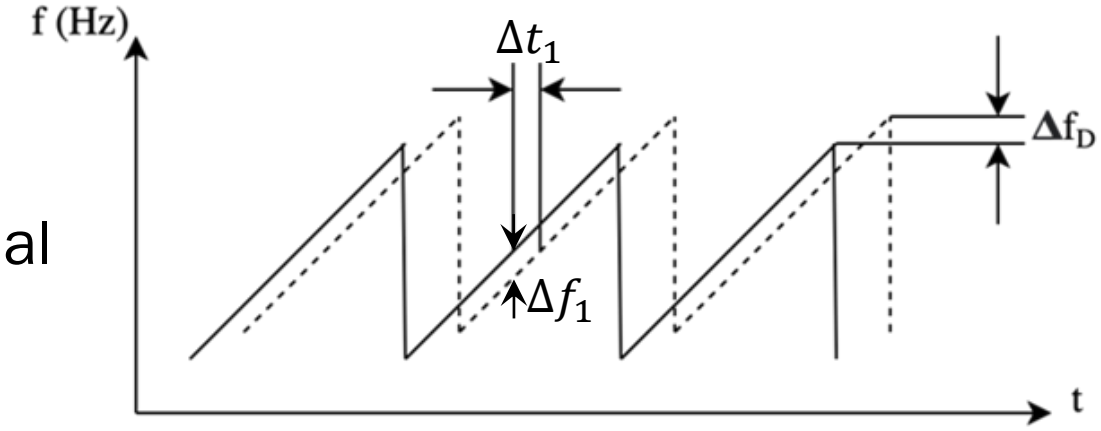



$$R = c_0 \frac{|\Delta t|}{2} = c_0 \frac{|\Delta F|}{2} \frac{\mathrm{d}t}{\mathrm{d}F}$$

# What's the math behind it?

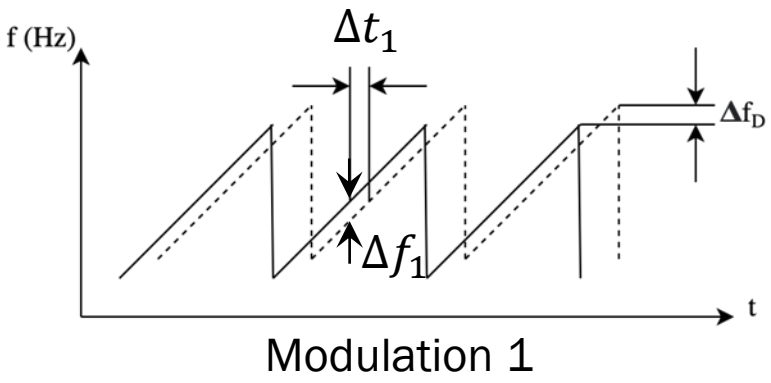
The distance of a detection $R$ is proportional to the ToF of the wave $\frac{\Delta t}{2}$, which can be calculated from the frequency shift wave $\Delta F$ and the slope of the modulation.

For a moving target, the Doppler effect will perturb $\Delta F$, and thus perturb the measure $R$.

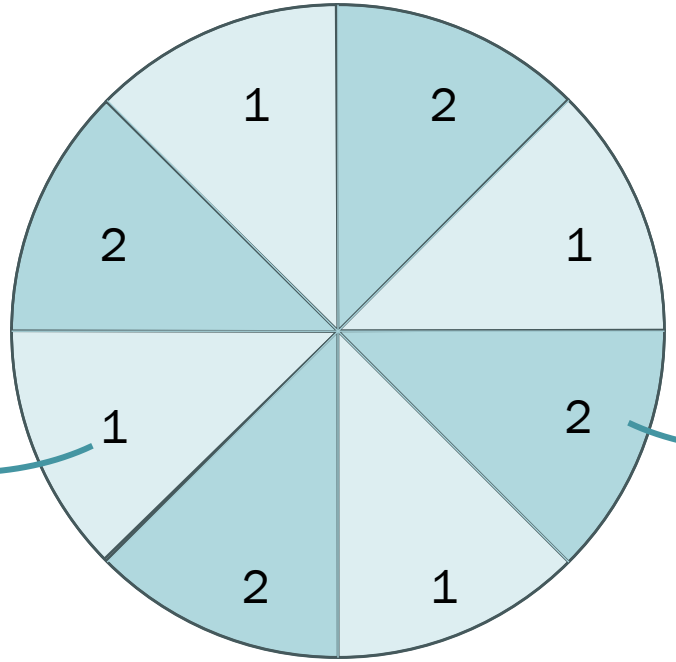


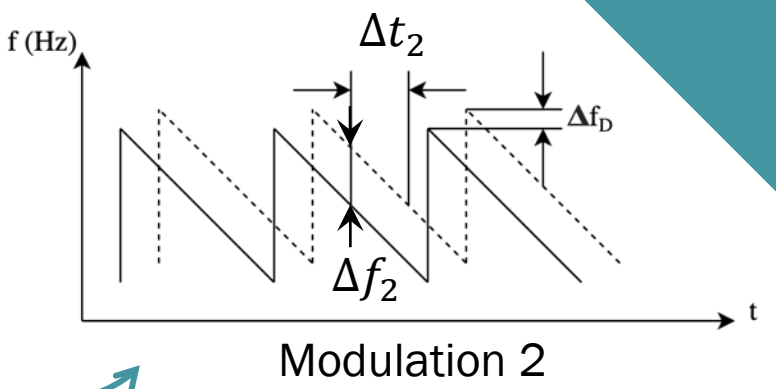

$$R + dR = c_0 \frac{|\Delta F + dF|}{2} \frac{\mathrm{d}t}{\mathrm{d}F}$$

# The Doppler effect




Modulation 1




Modulation 2

$$c_0 \frac{|\Delta F + dF|}{2} \frac{\mathrm{d}t}{\mathrm{d}F} = \mathrm{R} + \mathrm{dR}$$

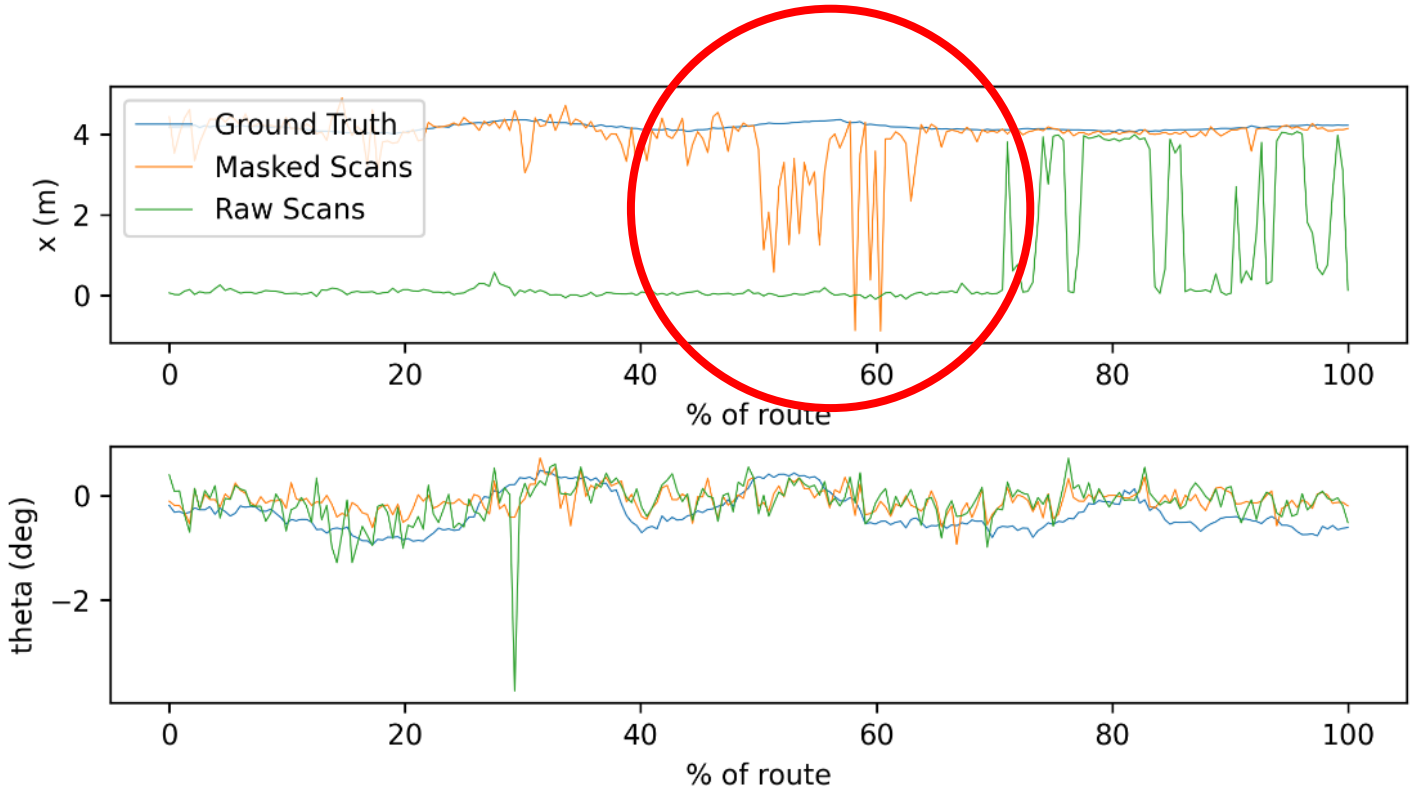
$$c_0 \frac{|\Delta F + dF|}{2} \frac{\mathrm{d}t}{\mathrm{d}F} = \mathrm{R} - \mathrm{dR}$$

Opposite Doppler effect on range!

# Results on odometry

Improved results against no masking (raw) or no Doppler.

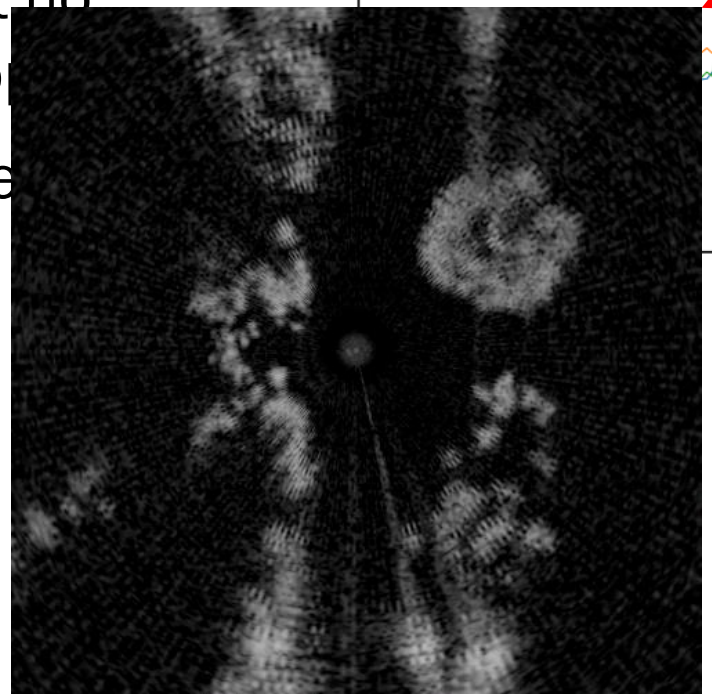
But still failing badly in feature-poor sceneries!

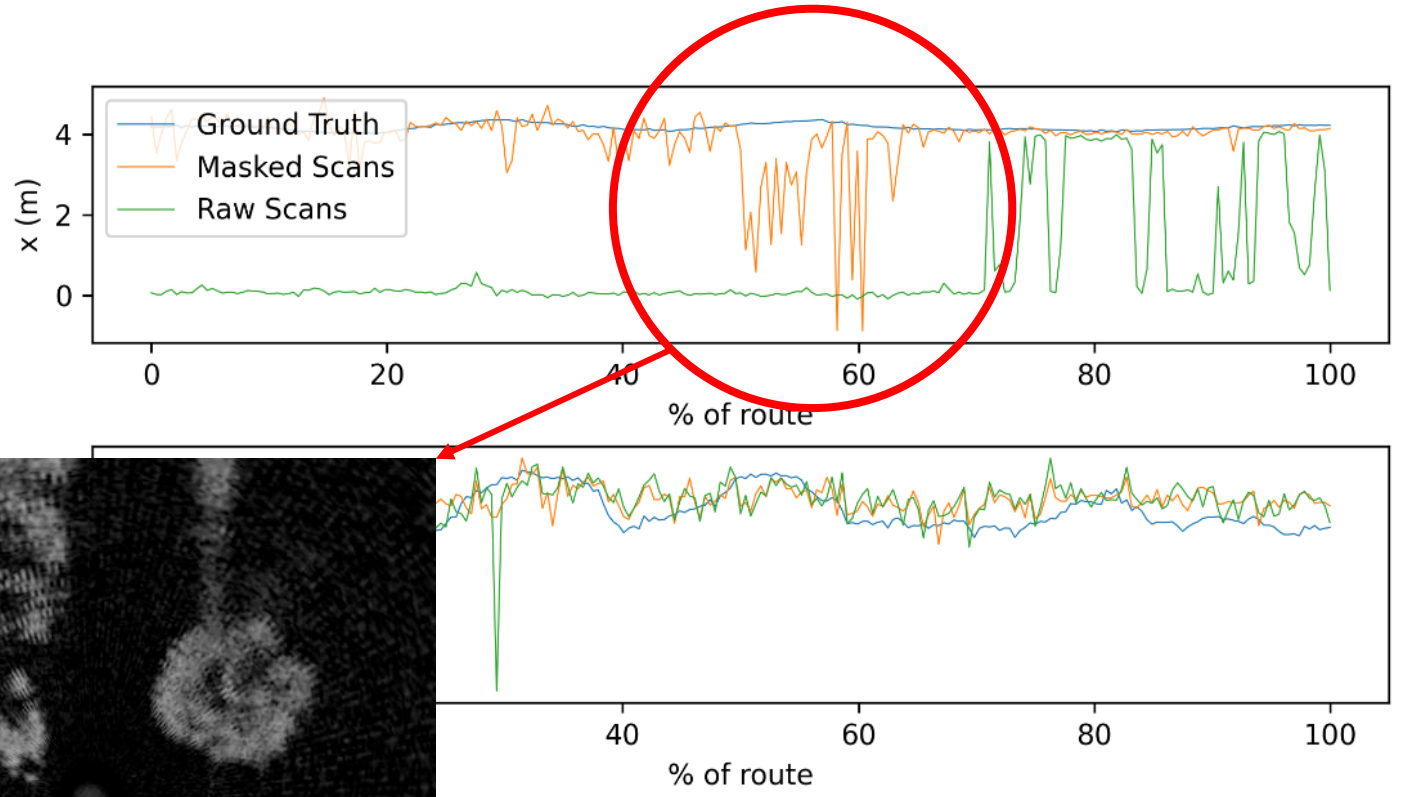


# Results on odometry

Improved results against no masking (raw) or no Dopp

But still failing badly in fe poor sceneries!



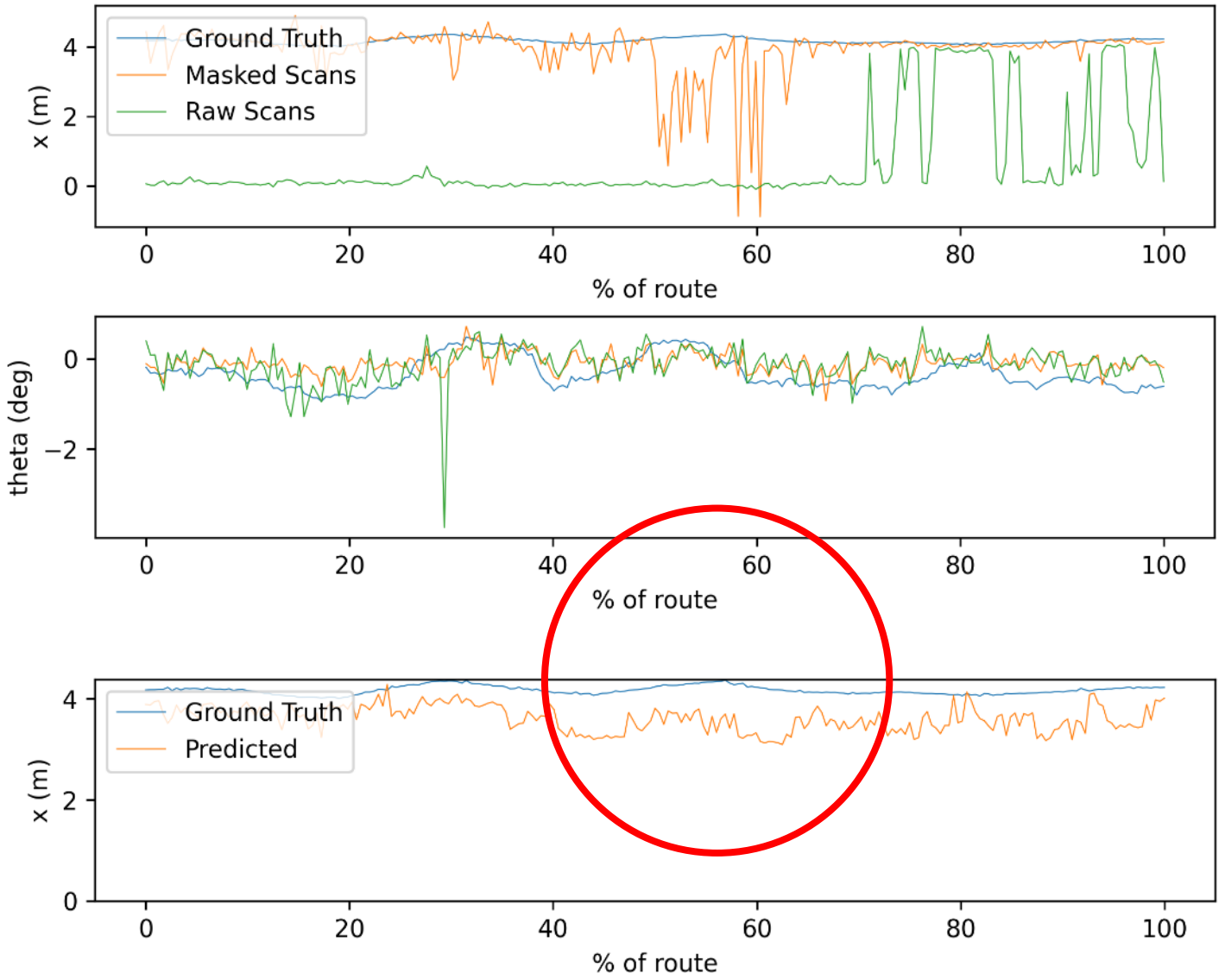


# Results on odometry

Improved results against no masking (raw) or no Doppler.

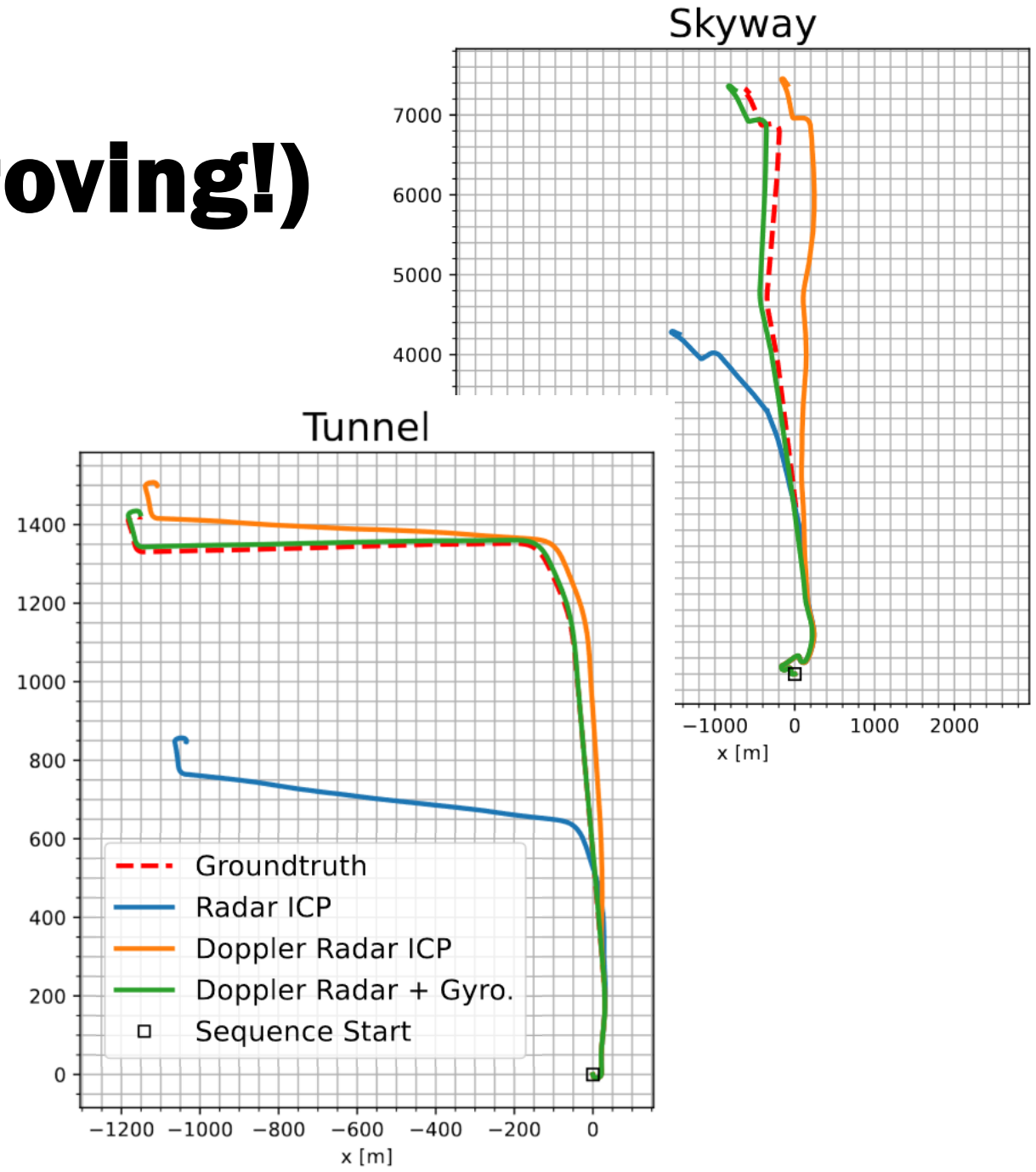
But still failing badly in feature-poor sceneries!

Doppler does not fail even using a very naïve velocity regressor on raw data, but it is less accurate.



# Doppler is already spreading (and improving!)

"*Are Doppler Velocity Measurements Useful for Spinning Radar Odometry?*" by D. Lisus, K. Burnett, D. Yoon, and T. Barfoot



# The Husky-X project

Study how climate change affects grassland growth and diversification.

Collaboration with GOALS and the Department of Biology.


SalGo

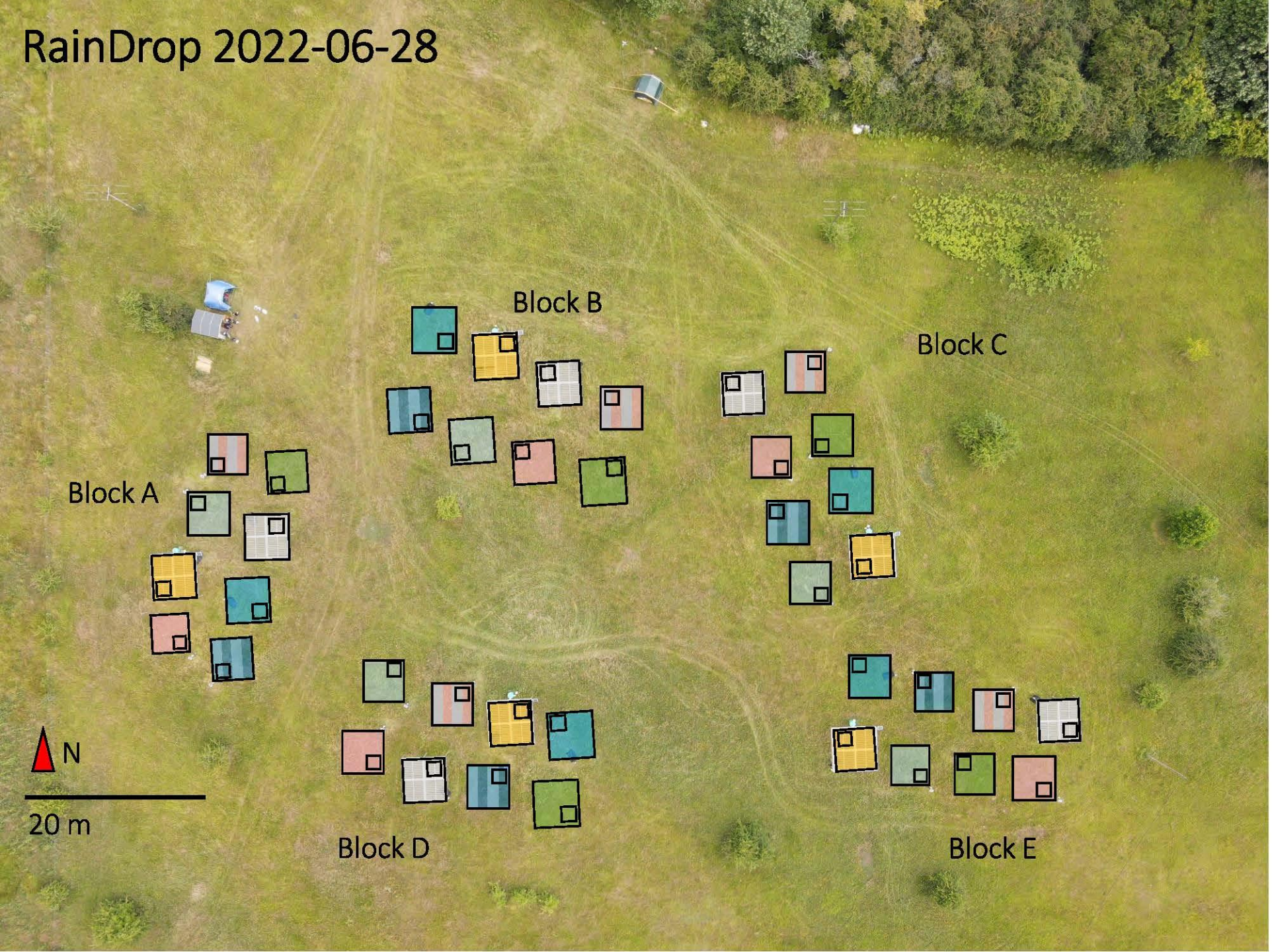
GOAL-ORIENTED AUTONOMOUS LONG-LIVED SYSTEMS
OXFORD ROBOTICS INSTITUTE

MRG
MOBILE ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE

# The Husky-X project


GOAL-ORIENTED AUTONOMOUS LONG-LIVED SYSTEMS
OXFORD ROBOTICS INSTITUTE

MRG
MOBILE ROBOTICS GROUP
OXFORD ROBOTICS INSTITUTE



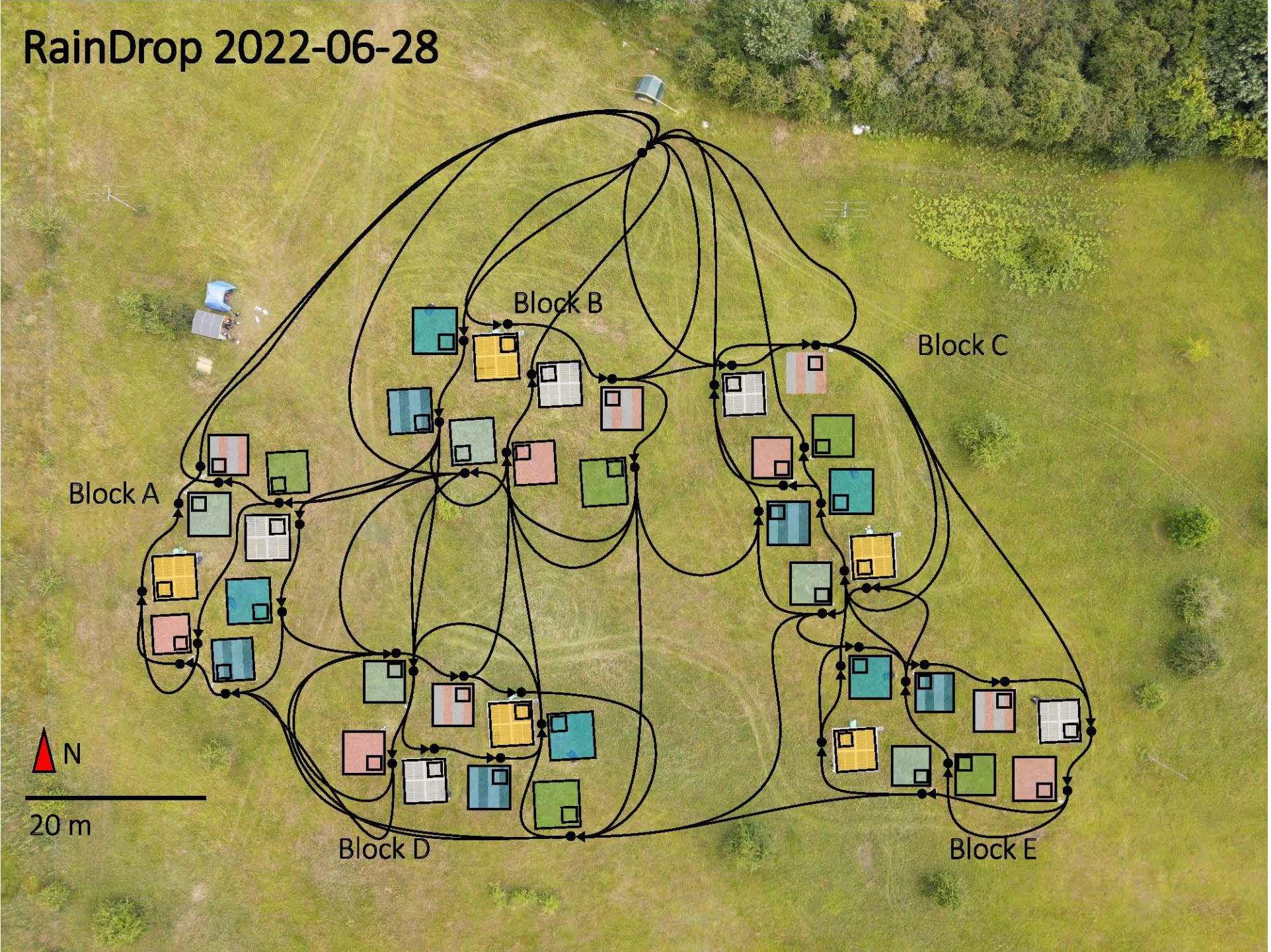

## Legend

### DroughtNet

- Drought
- Irrigation
- Procedural Control
- Ambient Control

### DRAGNet

- Disturbance
- NPK
- NPK + Disturbance
- NPK Cessation




## Legend

### DroughtNet

- Drought
- Irrigation
- Procedural Control
- Ambient Control

### DRAGNet

- Disturbance
- NPK
- NPK + Disturbance
- NPK Cessation

# Open up applications

The new small form factor can open up new applications with smaller robotic platforms.

# Some final thoughts

Leading towards the final discussion panel

# What areas are un- or lightly explored?

Radar specific architectures

Simulation

Sensor fusion

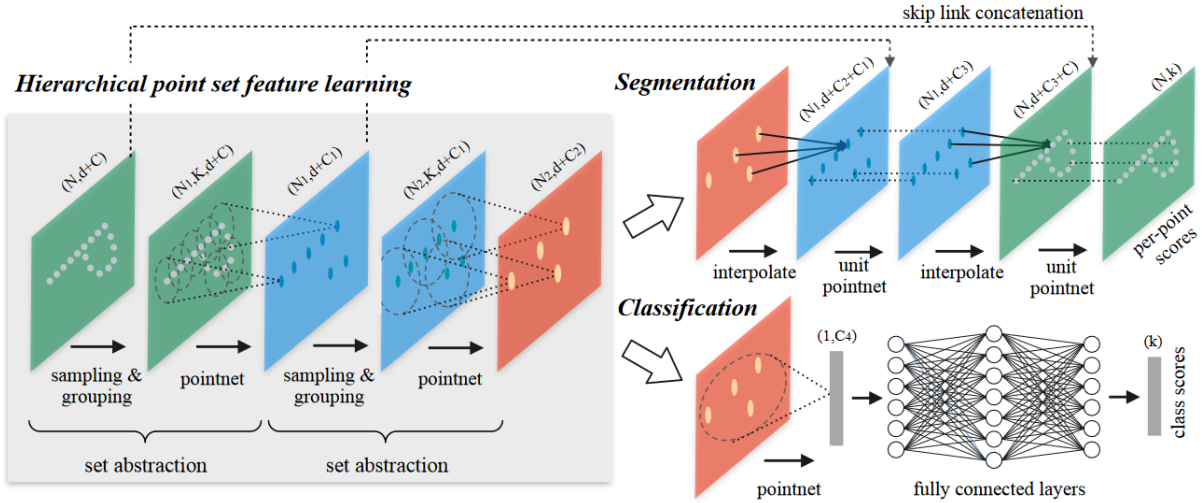
Foundational models

Recover physical properties

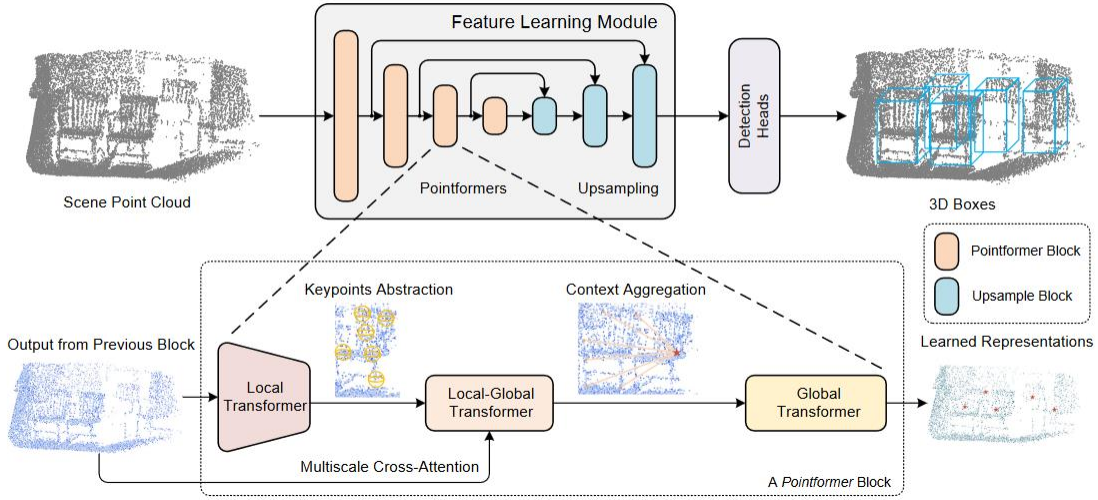
Dynamic/active configuration

# Radar specific architectures

Similarly to how LiDAR started adopting CNNs, is it the case for more specific networks that exploit radar properties?



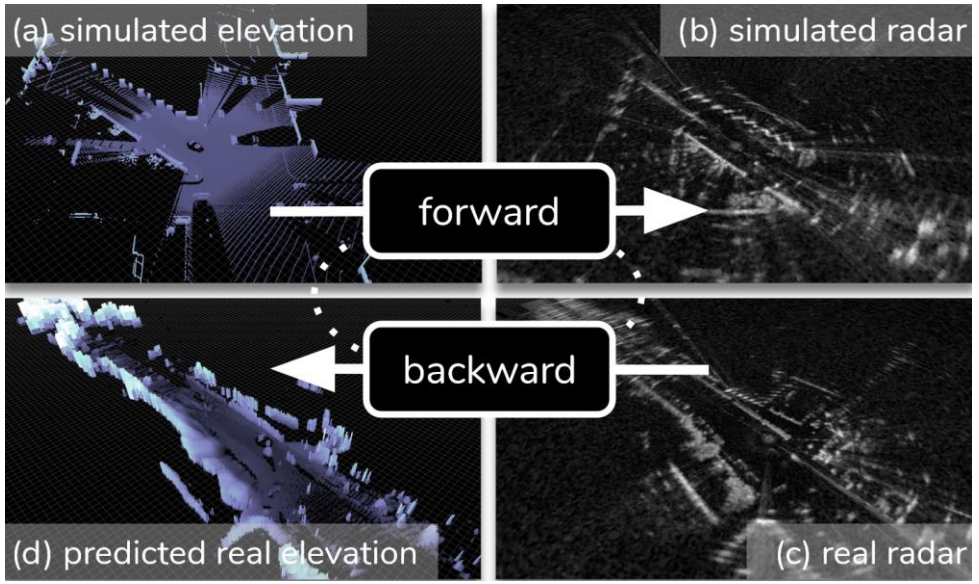

PointNet++



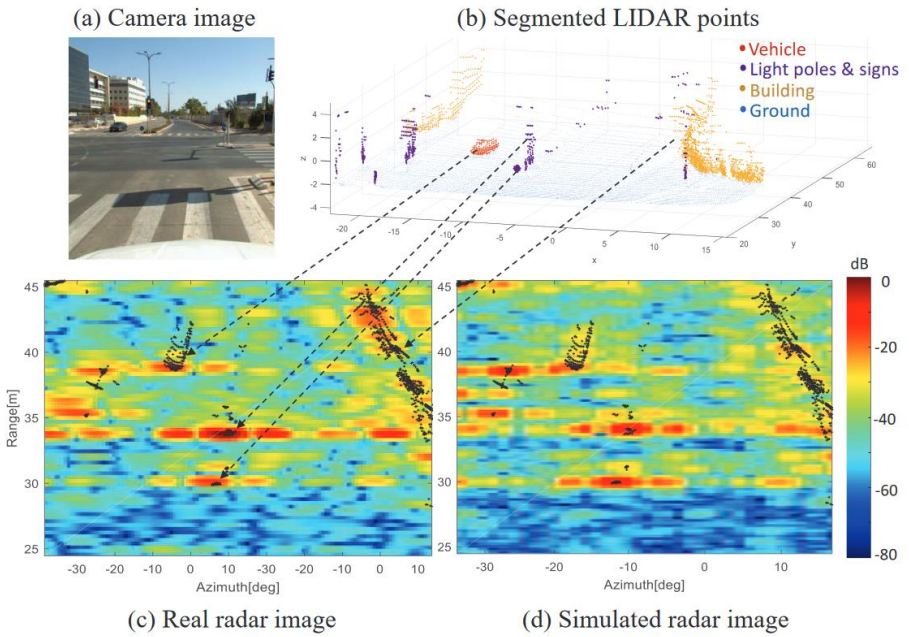

PointFormer

# Simulation

Simulation is pushing autonomy, especially connecting sensing and control through reinforcement learning. How can we simulate radar reliably?



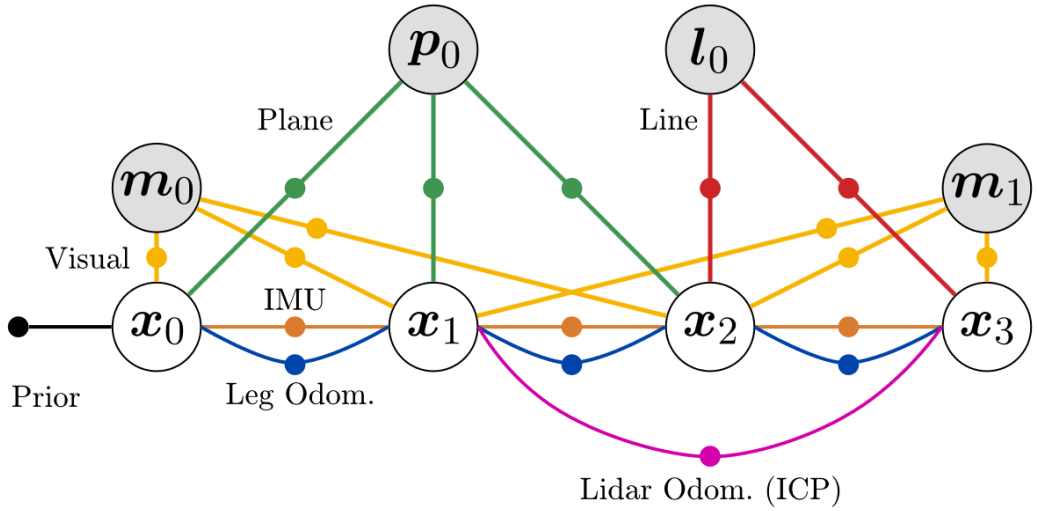

There and back again



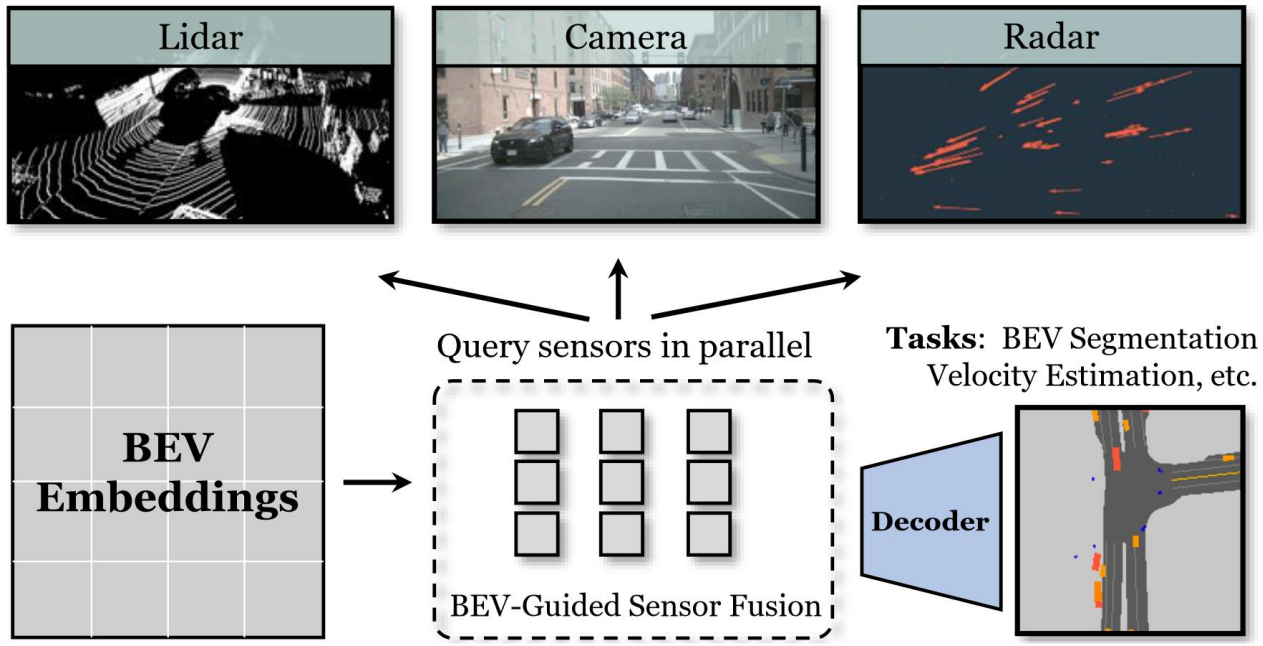

RadSimReal

# Sensor fusion

Cameras, lidar and radar have complementary characteristics. Fusing/selecting the sensors could lead to better performances?




VILENS




BEVGuide

# Foundational models

Following the vision community, foundational models gave a huge boost to research. Can we build one for radar?

Segment anything

dinov2

# Foundational models

Following the vision community, foundational models gave a huge boost to research. Can we build one for radar? And maybe incorporate text?

What is the colour of the shirt the man is wearing?

The man is wearing a yellow shirt.

LLava

# Recover physical properties

What if we have only scratched the surface of radar's ability to understand the scene? Can we extract material properties from the signal?

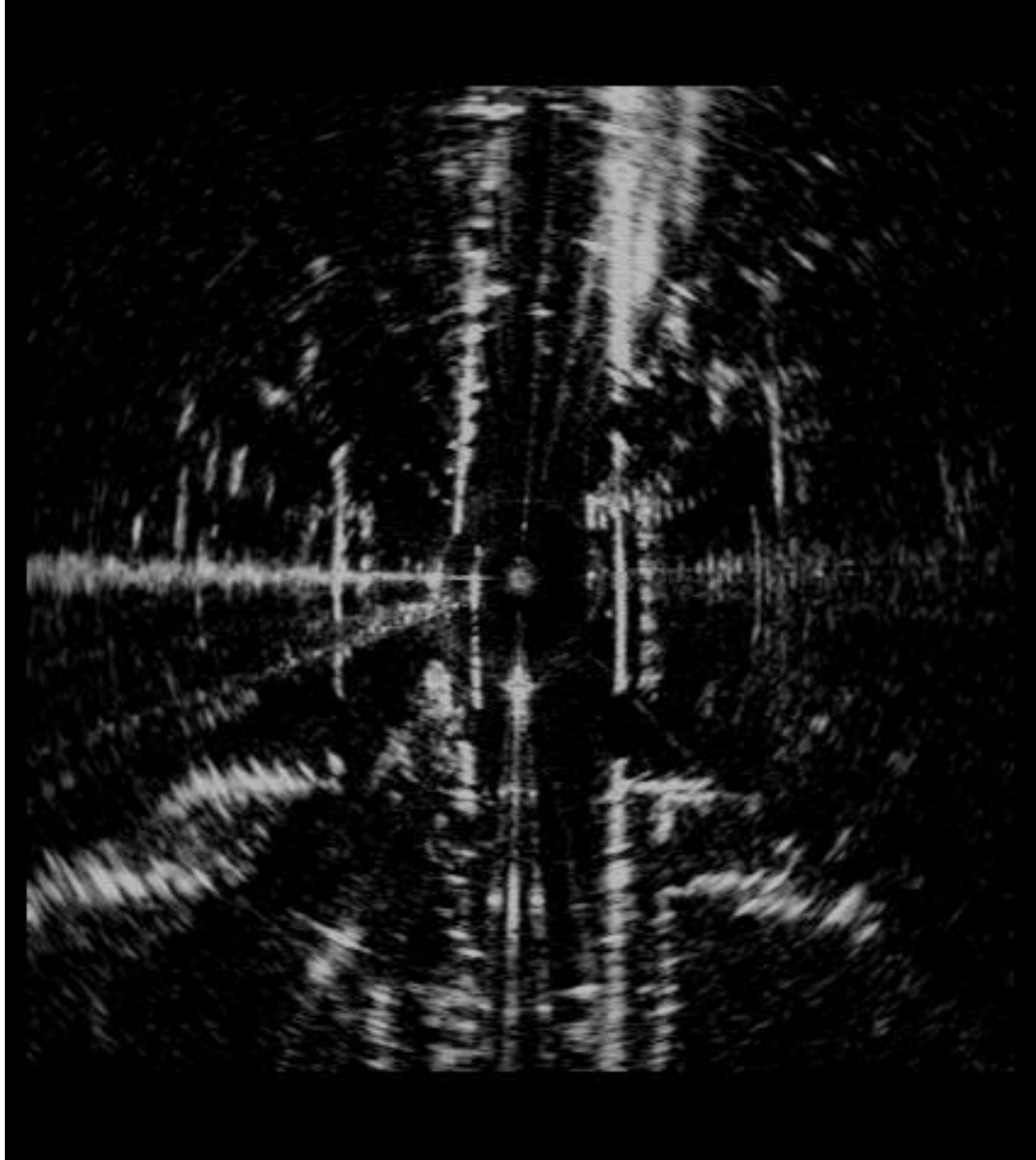
$$P_r = \frac{P_t G_t}{4\pi R^2} \frac{A_E \sigma}{4\pi R^2}$$

Radar cross-section σ depends on:

- Material
- Shape
- Roughness
- Incident angle (relative position)

# Dynamic/active configuration

Can we actively configure the radar sensor to give us the best data for the task at hand? Range, speed, wave shape.




# Thank you!

For further discussions, please contact me at daniele@robots.ox.ac.uk