MICHIGAN STATE UNIVERSITY

Multi-Pass Automotive Synthetic Aperture Radar Image Fusion

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delta
Distributed Electromagnetics Theory and Applications

emrg
Electromagnetics Research Group
Michigan State University

Outline

1. Motivation & Background
2. Image Fusion
3. Data Collection
4. Experimental Results

Applications

Multi-Pass Automotive Synthetic Aperture Radar

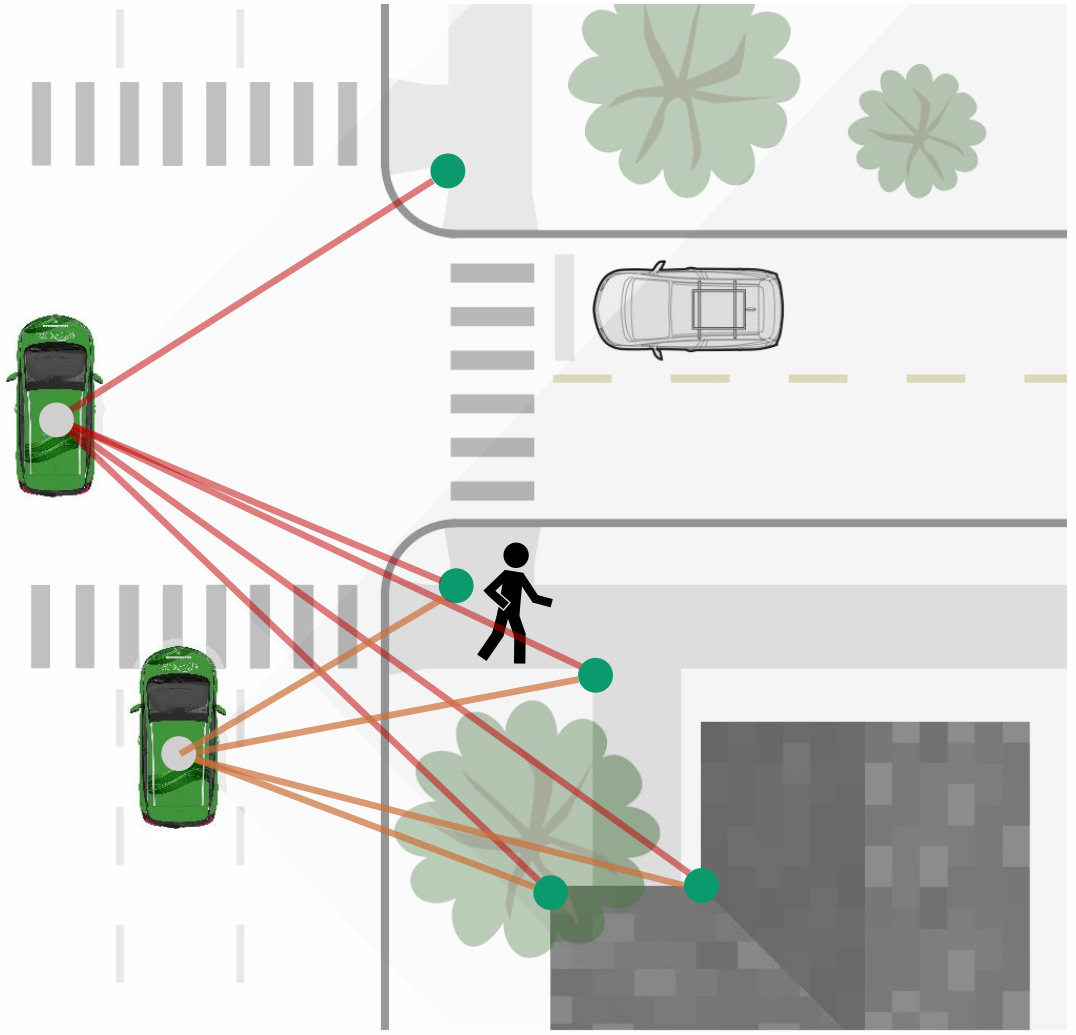
Slow ⟵ Revisiting Interval ⟶ Fast

Rapid revisiting interval (Cooperative)

- Increased spatial diversity and angular resolution
- Increased system gain
- Improved probability of detection
- Relative localization

Long revisiting interval

- Vehicle localization and odometry
- Road change/hazard detection

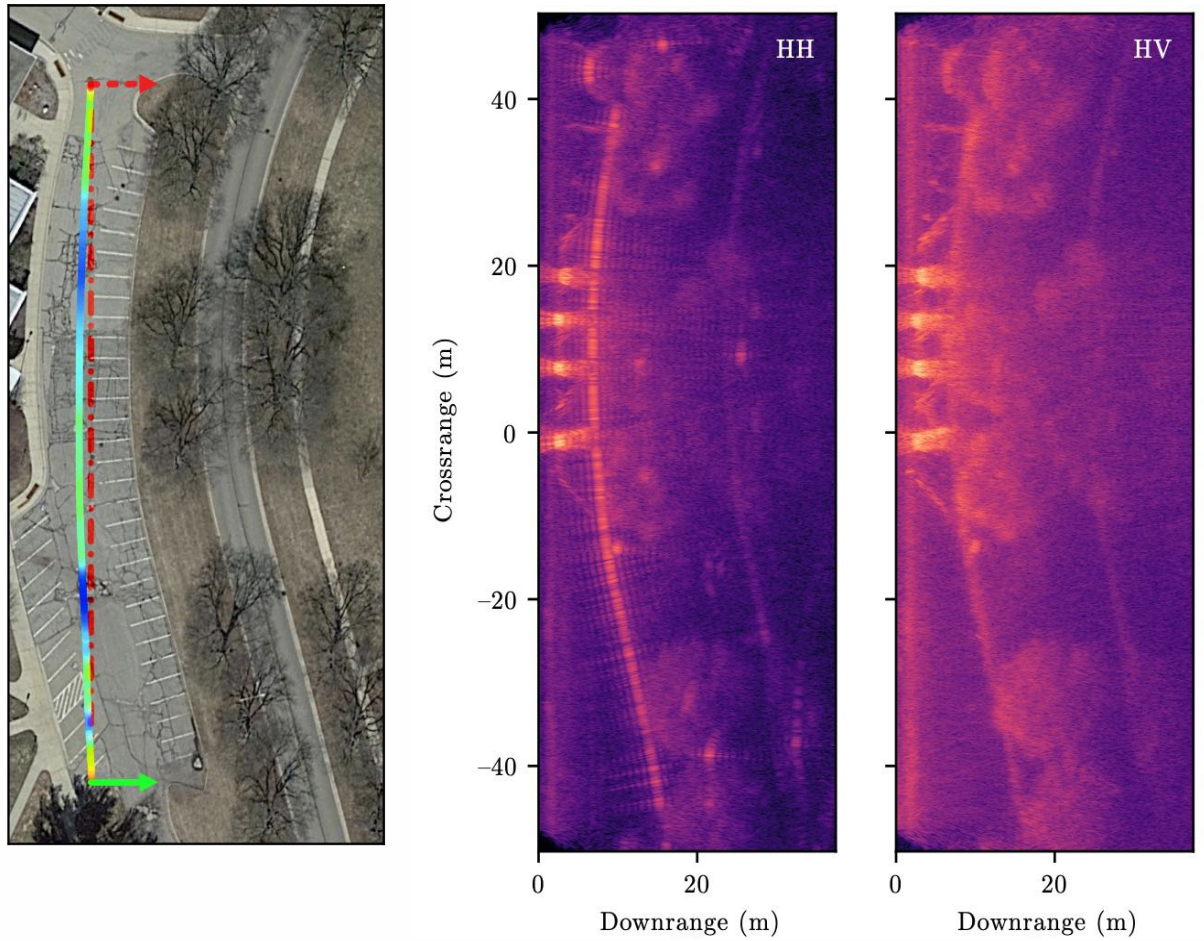


Radar Map Landmarks

Motivation of This Work

- Automated vehicles require accurate localization and environmental awareness
- Vehicles are becoming more connected (V2X)
- Can we reuse existing communications frequencies for sensing on AVs?

C-Band Automotive SAR Images



J. M. Merlo and J. A. Nanzer, "A C-Band Fully Polarimetric Automotive Synthetic Aperture Radar," in *IEEE Transactions on Vehicular Technology*, vol. 71, no. 3, pp. 2587-2600, March 2022, doi: 10.1109/TVT.2021.3138348.

Image Formation Algorithm

Range Migration Algorithm (RMA / Omega-k)

- ✓ Efficient image formation using Fast Fourier Transforms (FFTs)
- ✓ Focuses well across all ranges (large depth of field)
- ✓ Focuses well across with wide imaging swaths (wide field of view)
- ✗ Requires uniform sampling along cross-range axis

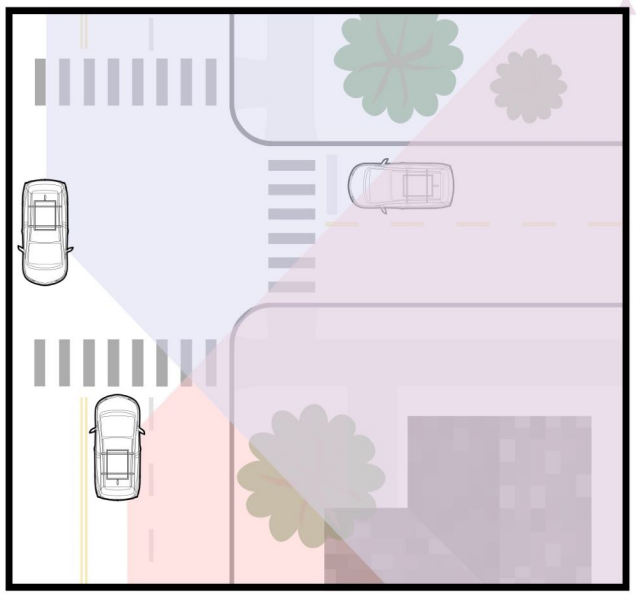
Possible solutions:

a. Use an inverse method to form image from nonuniform samples (*if* accurate sample locations are available)

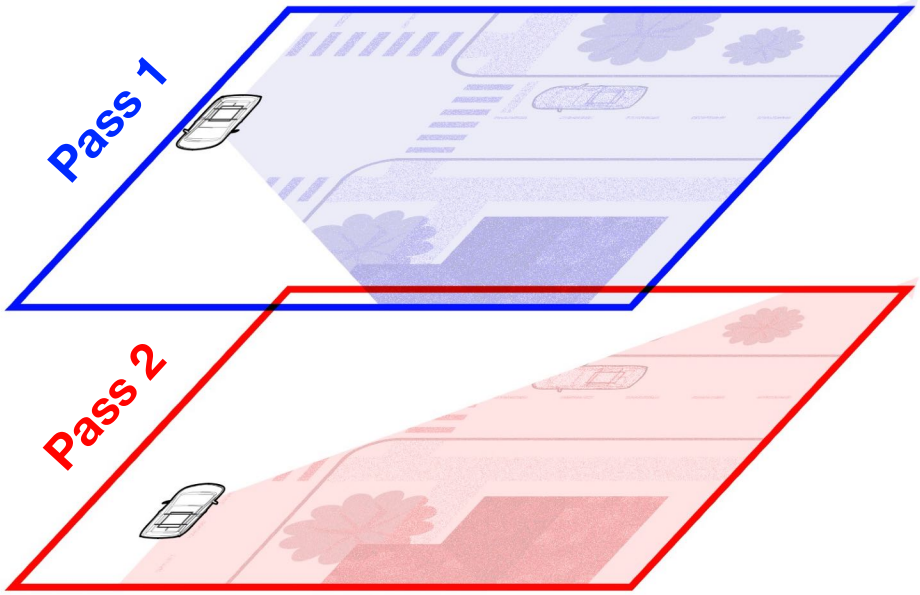
b. Correct for scene distortion using a reference image
   - \+ Provides sub-aperture motion vector corrections for odometry and localization
   - \+ Provides stacked global/relative referenced SAR images for further processing

Synthetic Aperture Image Fusion

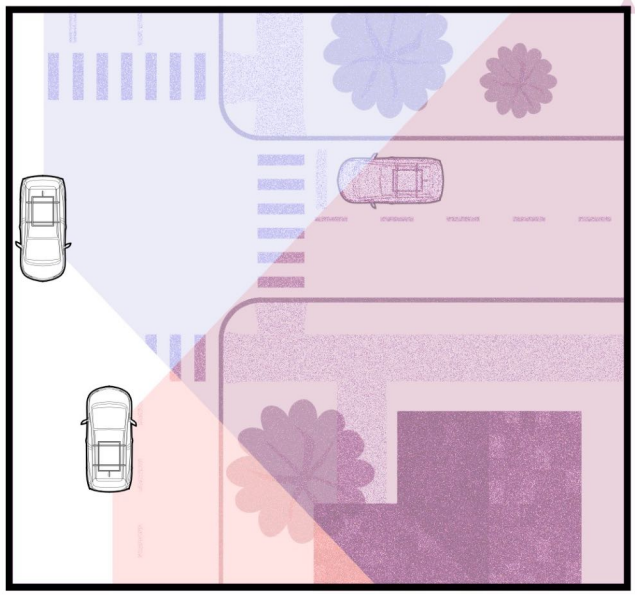
Multi-pass SAR Image



Align and Stack

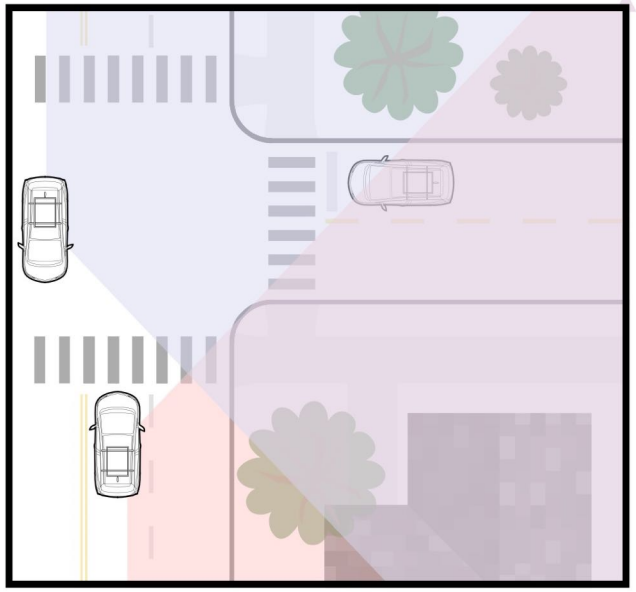


Incoherent Summation



Synthetic Aperture Image Fusion

Multi-pass SAR Image



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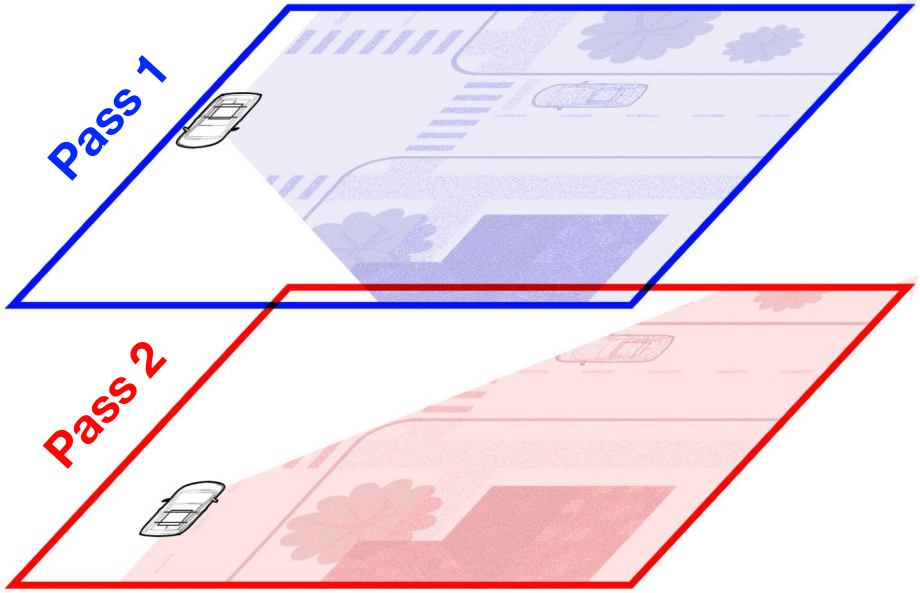


Incoherent Summation

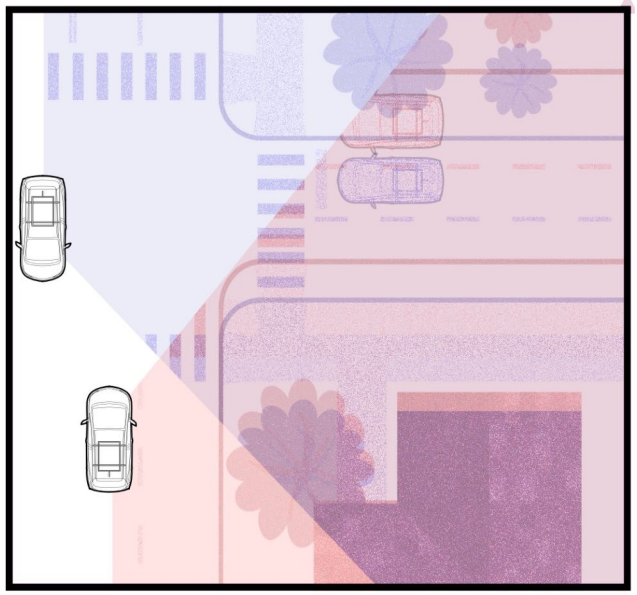


Image Fusion

2D Correlation-Based Image Alignment

- Translates scene along x and y axes to point of maximum correlation

$$r_{fg}(x_0, y_0) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) g^*(x - x_0, y - y_0)$$

$$= \mathcal{F}^{-1}\{F(x,y) G^*(x,y)\}$$

where

- M, N are the image width and height, respectively
- F and G are the Fourier transform pairs of f and g

[1] M. Guizar-Sicairos, S. T. Thurman, and J. R. Fienup, “Efficient subpixel image registration algorithms,” Opt. Lett., vol. 33, no. 2, pp. 156–158, Jan 2008. [Online]. Available: https://opg.optica.org/ol/ abstract.cfm?URI=ol-33-2-156

Image Fusion

2D Correlation-Based Image Alignment

- Translates scene along x and y axes to point of maximum correlation

$$\overrightarrow{r_{\text{align}}}(f,g) = \underset{x_0,y_0}{\text{argmax}}\left|r_{fg}(x_0,y_0)\right|$$

[1] M. Guizar-Sicairos, S. T. Thurman, and J. R. Fienup, “Efficient subpixel image registration algorithms,” Opt. Lett., vol. 33, no. 2, pp. 156–158, Jan 2008. [Online]. Available: https://opg.optica.org/ol/ abstract.cfm?URI=ol-33-2-156

Image Fusion

Full Scene Alignment

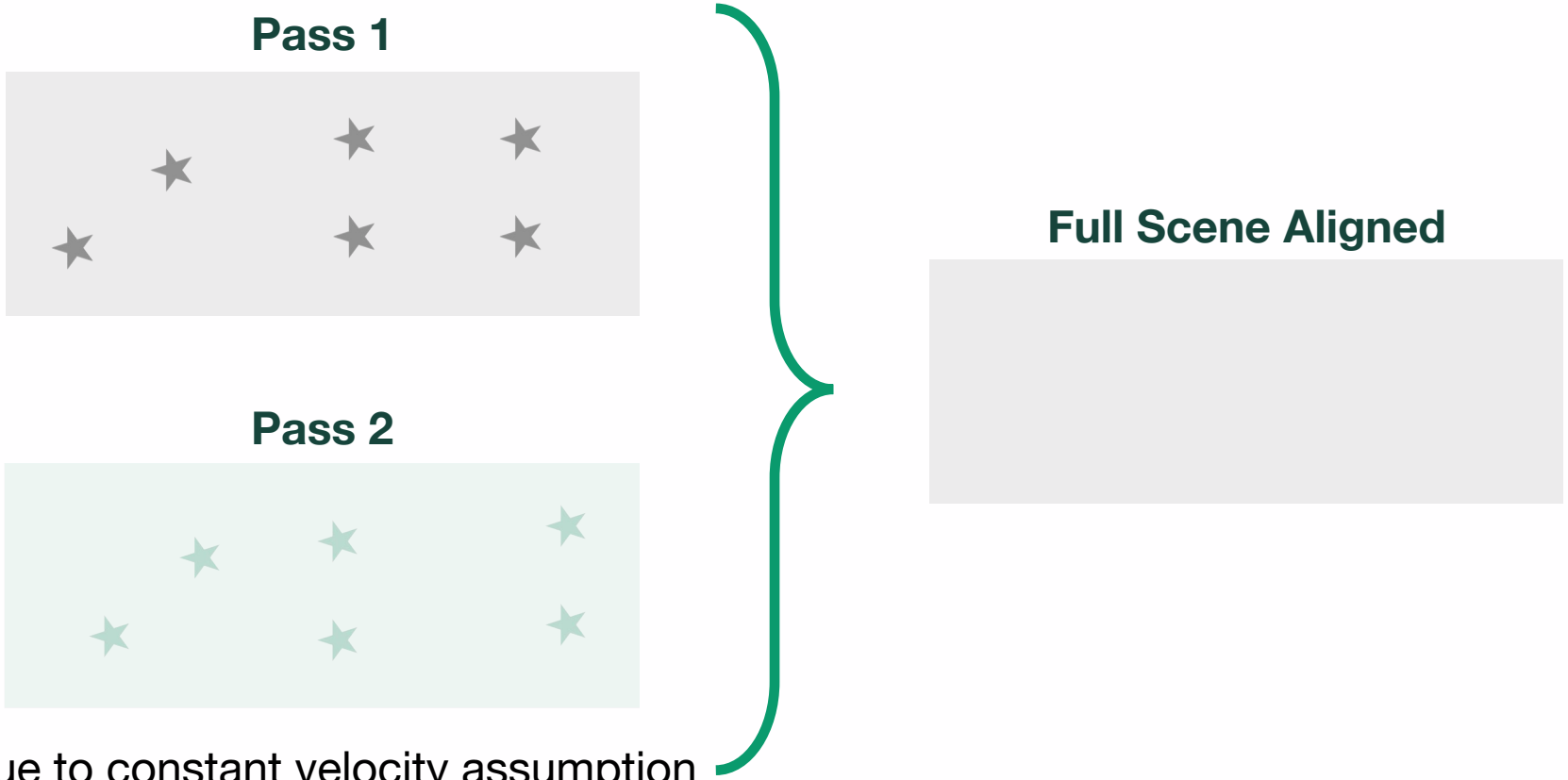


Image Fusion

Chunk Alignment

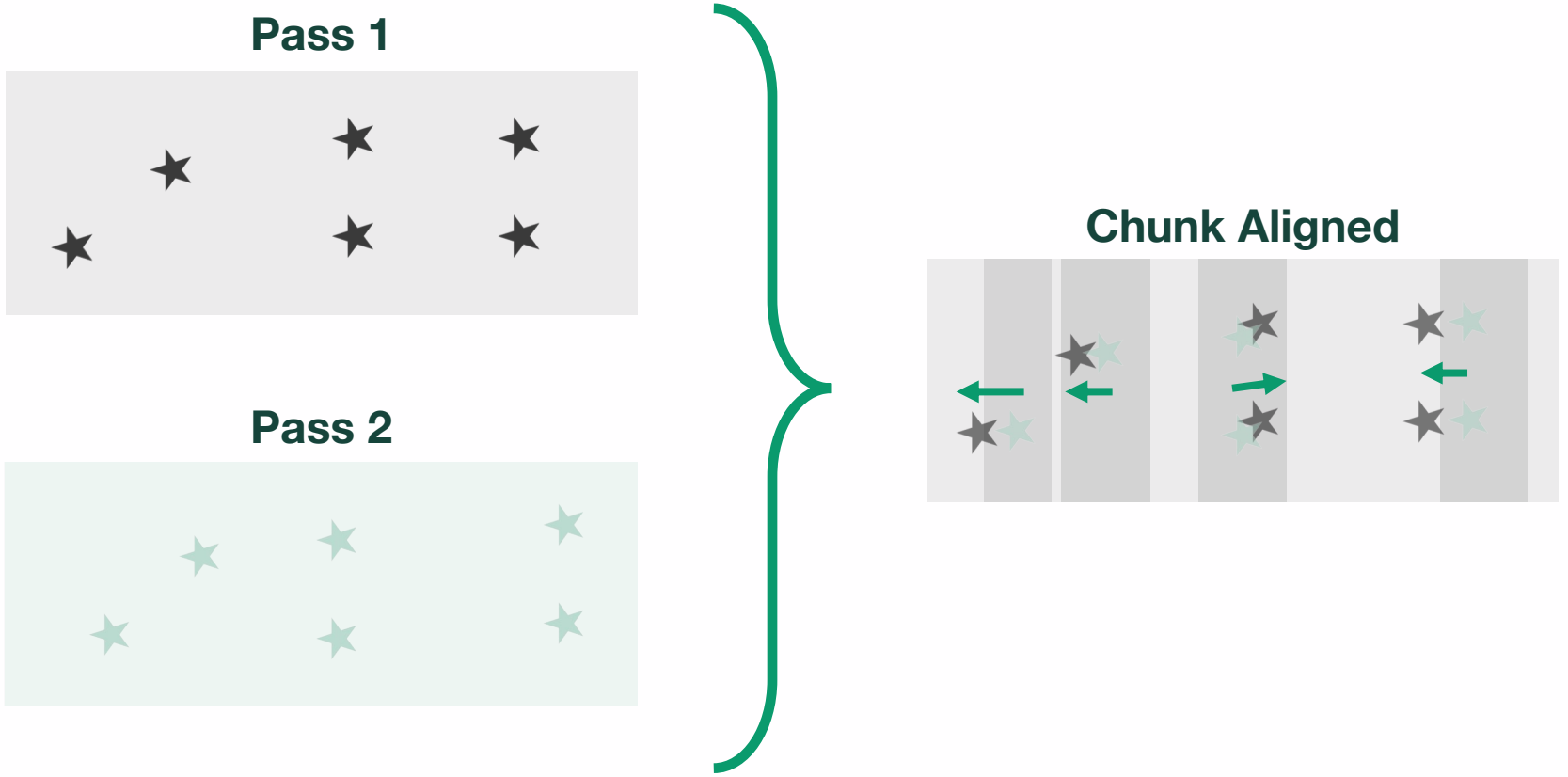
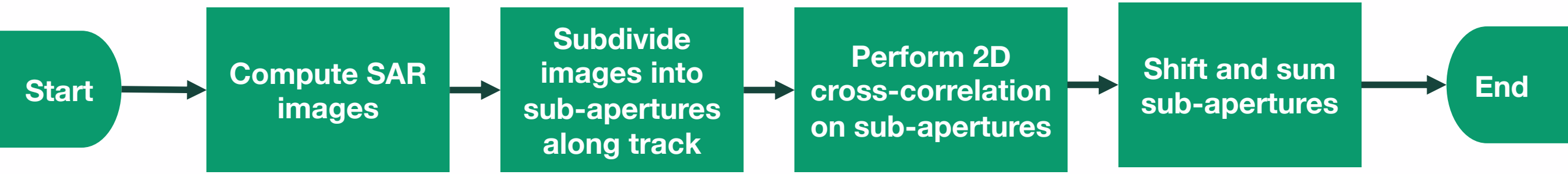


Image Fusion

Chunk Alignment Process



Data Collection System

System Architecture

- Frequency-modulated continuous-wave
- Direct downconversion
- Fully Polarimetric

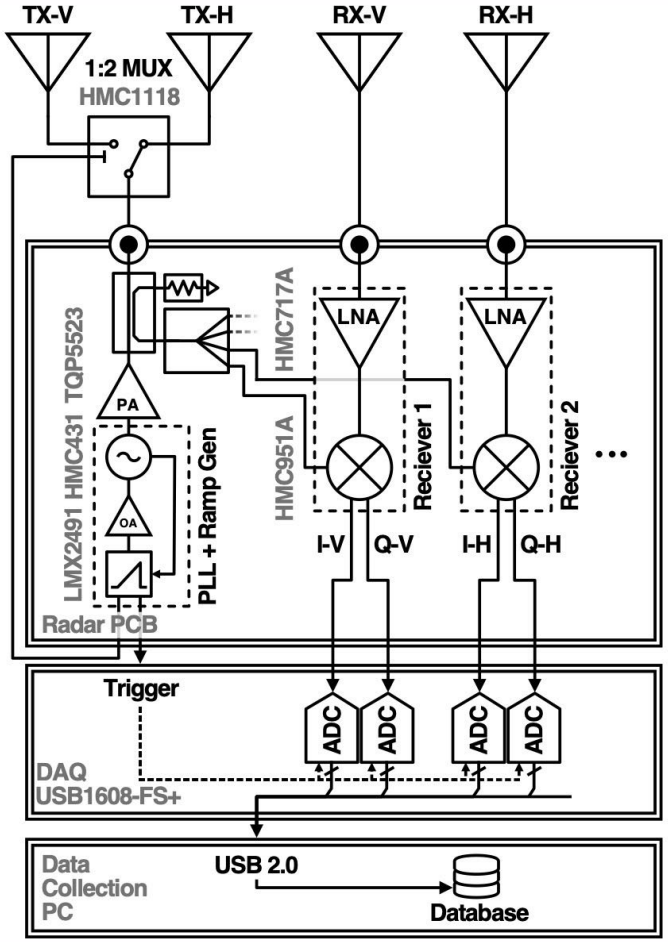
Waveform Parameters

- $f_c = 5.9$ GHz
- BW $= 200$ MHz
- $\tau_p = 1.0$ ms
- PRF $=$ ~75 Hz

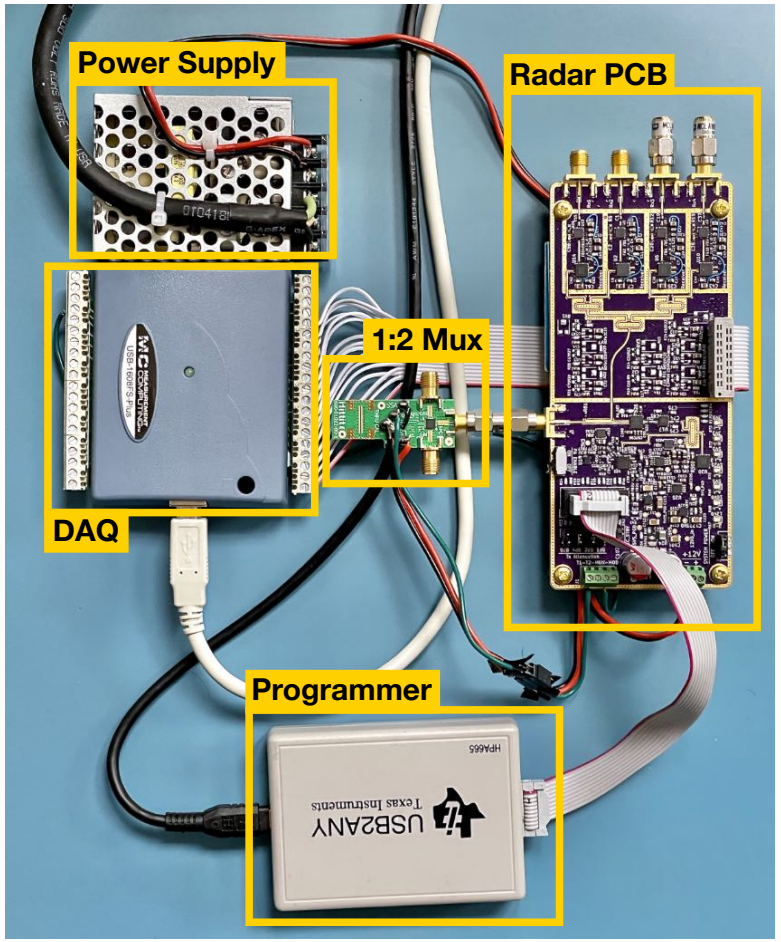
Data Acquisition

- $f_s = 100$ kSps/ch
- Software Triggered

Hardware Schematic

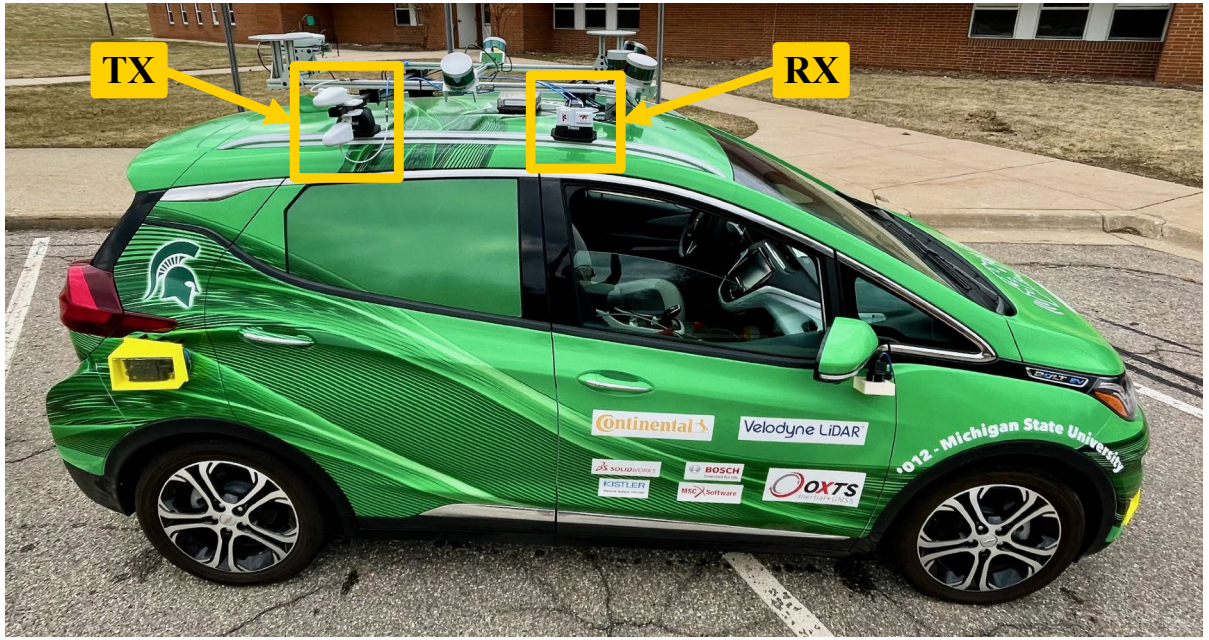


Assembled System

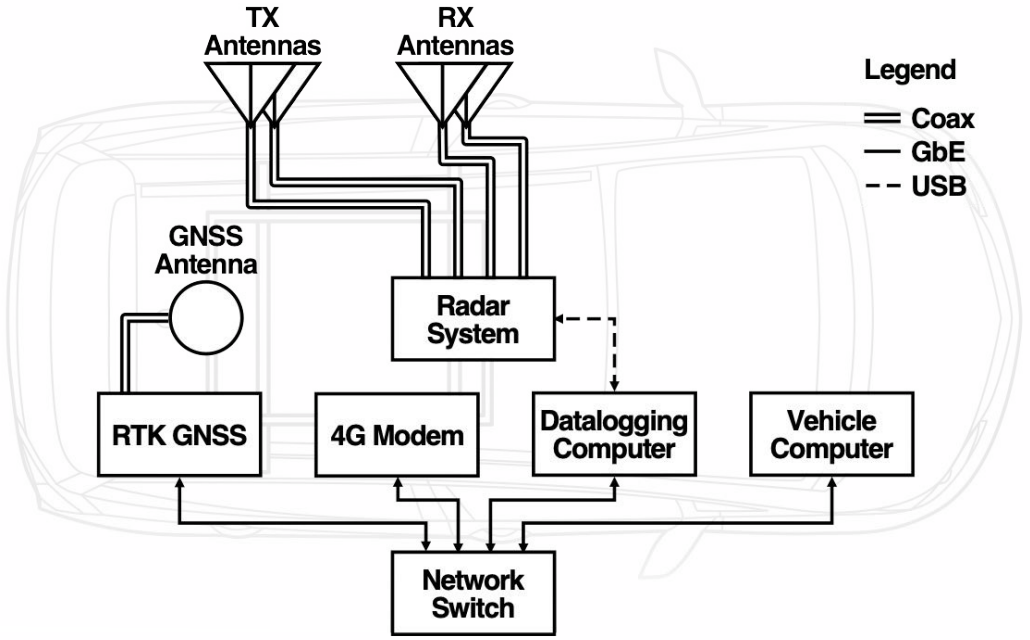


Data Collection Platform

MSU CANVAS Chevrolet Bolt AV



Platform Data Flow Architecture



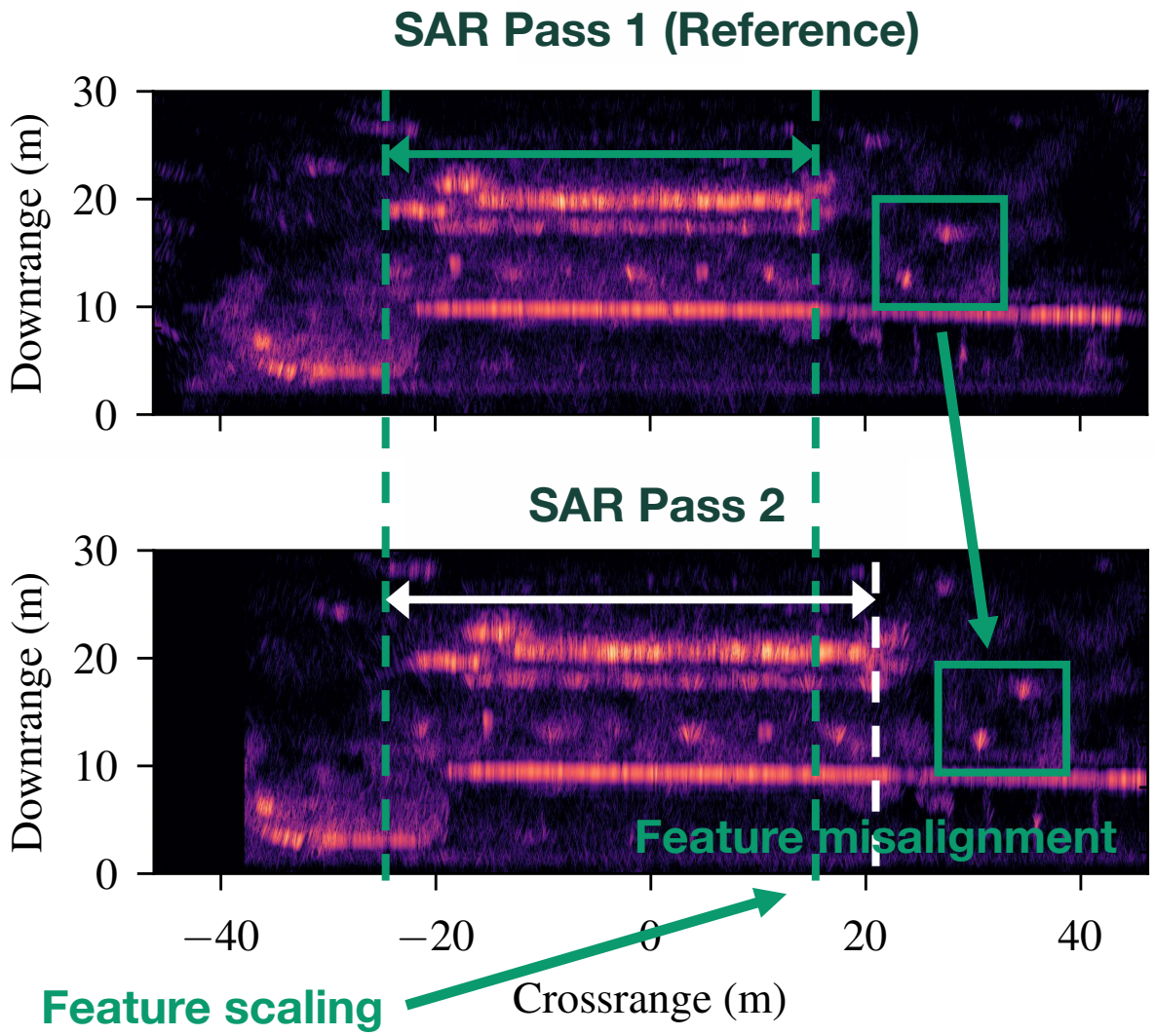
Antenna Parameters

- Transmit Antenna Gain: 13.2 dBi
- Receive Antenna Gain: 9.5 dBi
- Transmit Antenna HPBW: 40°
- Receive Antenna HPBW: 65°

Scene 1 | Two Passes

Spartan Village Autonomous Vehicle Test Facility, Michigan State University

Scene 1 | Two Passes



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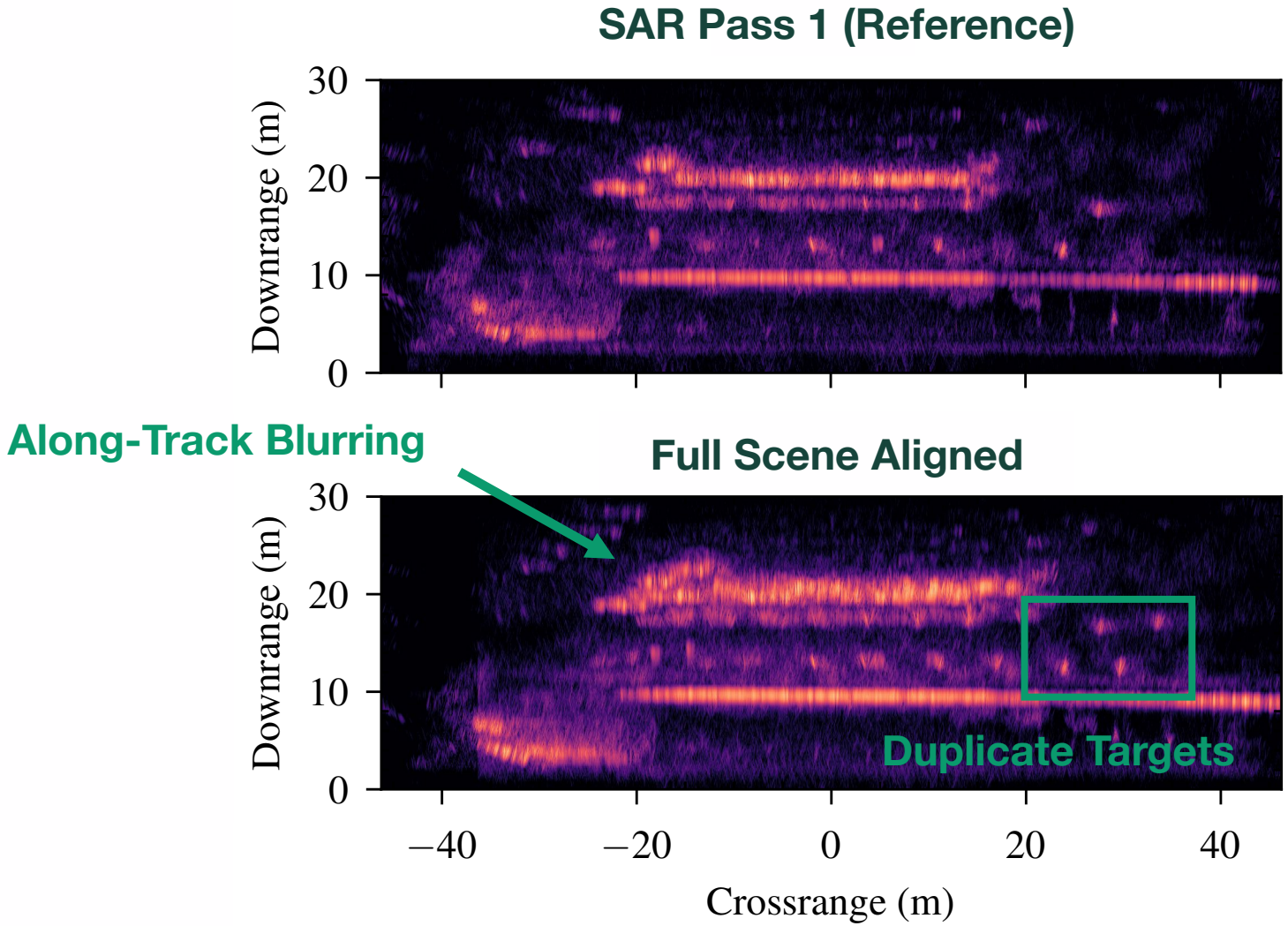

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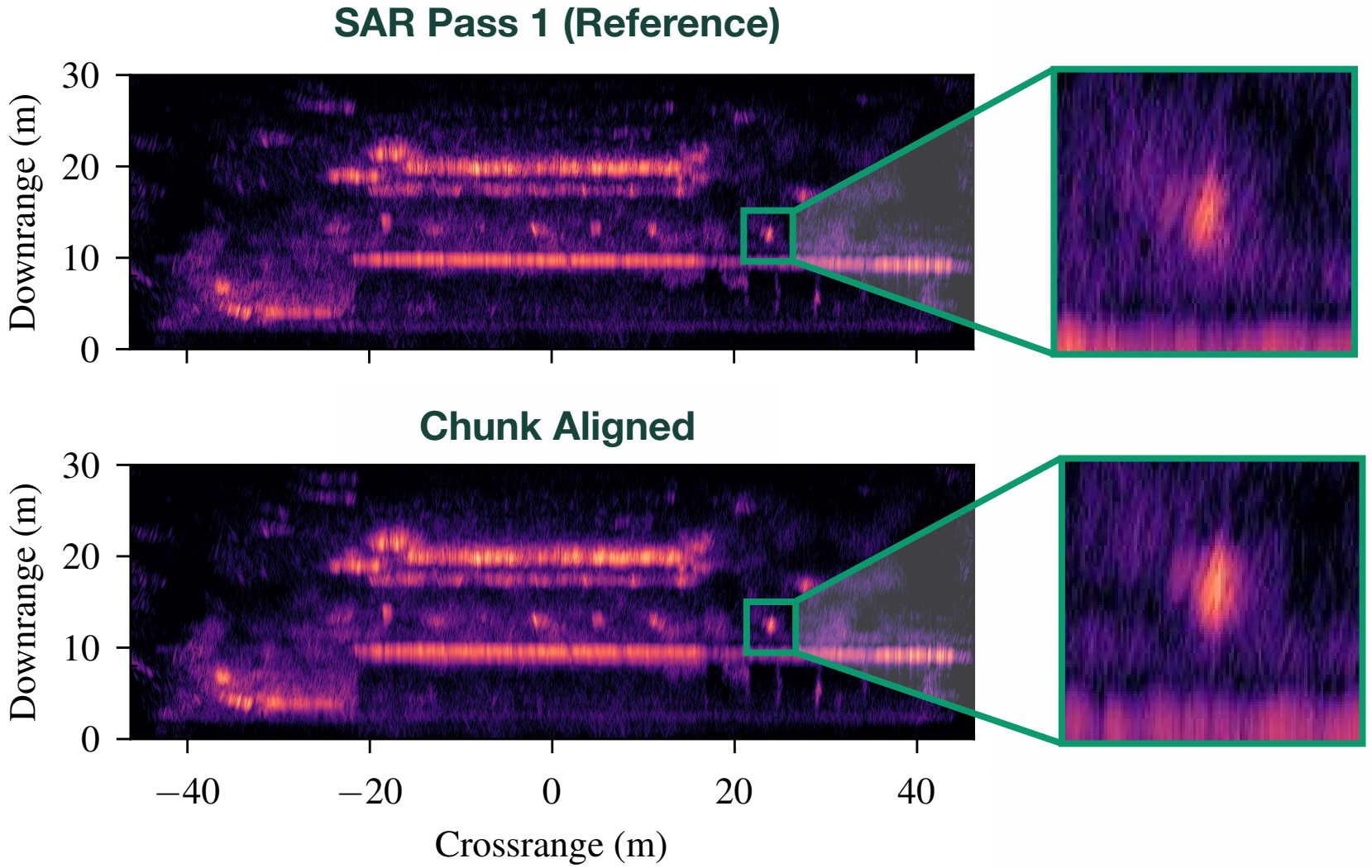
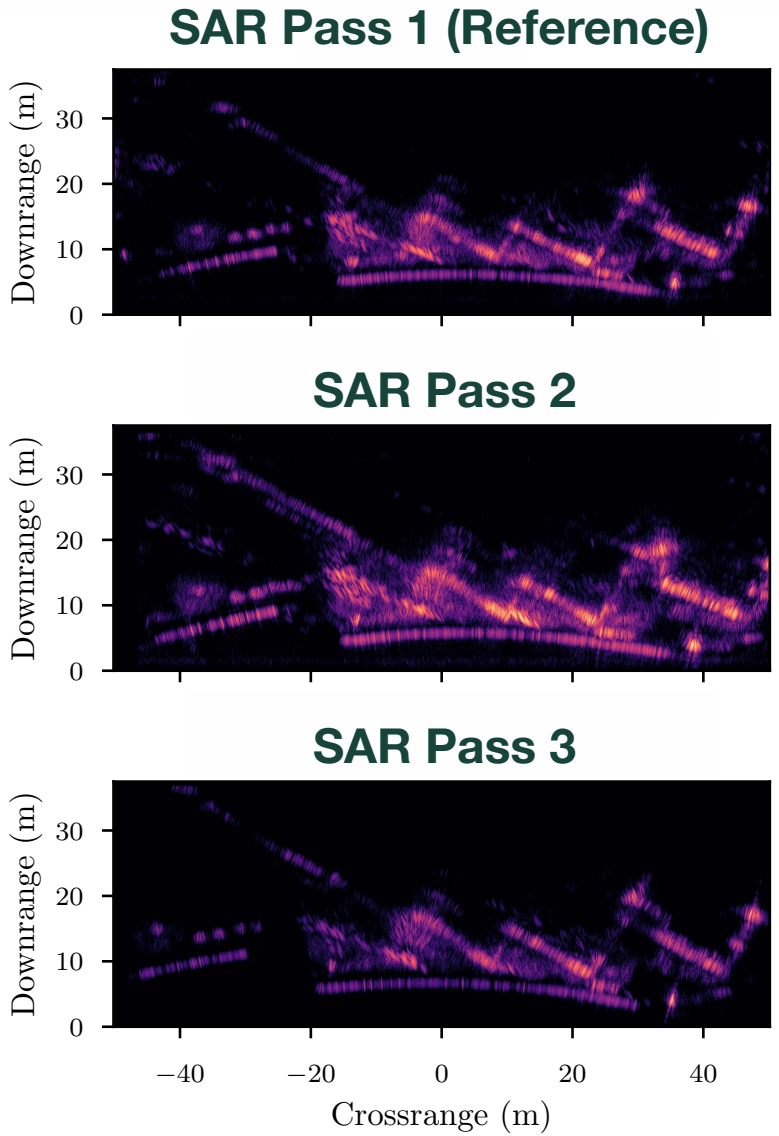


Scene 2 | Three Passes

Spartan Village Autonomous Vehicle Test Facility, Michigan State University

Scene 2 | Three Passes



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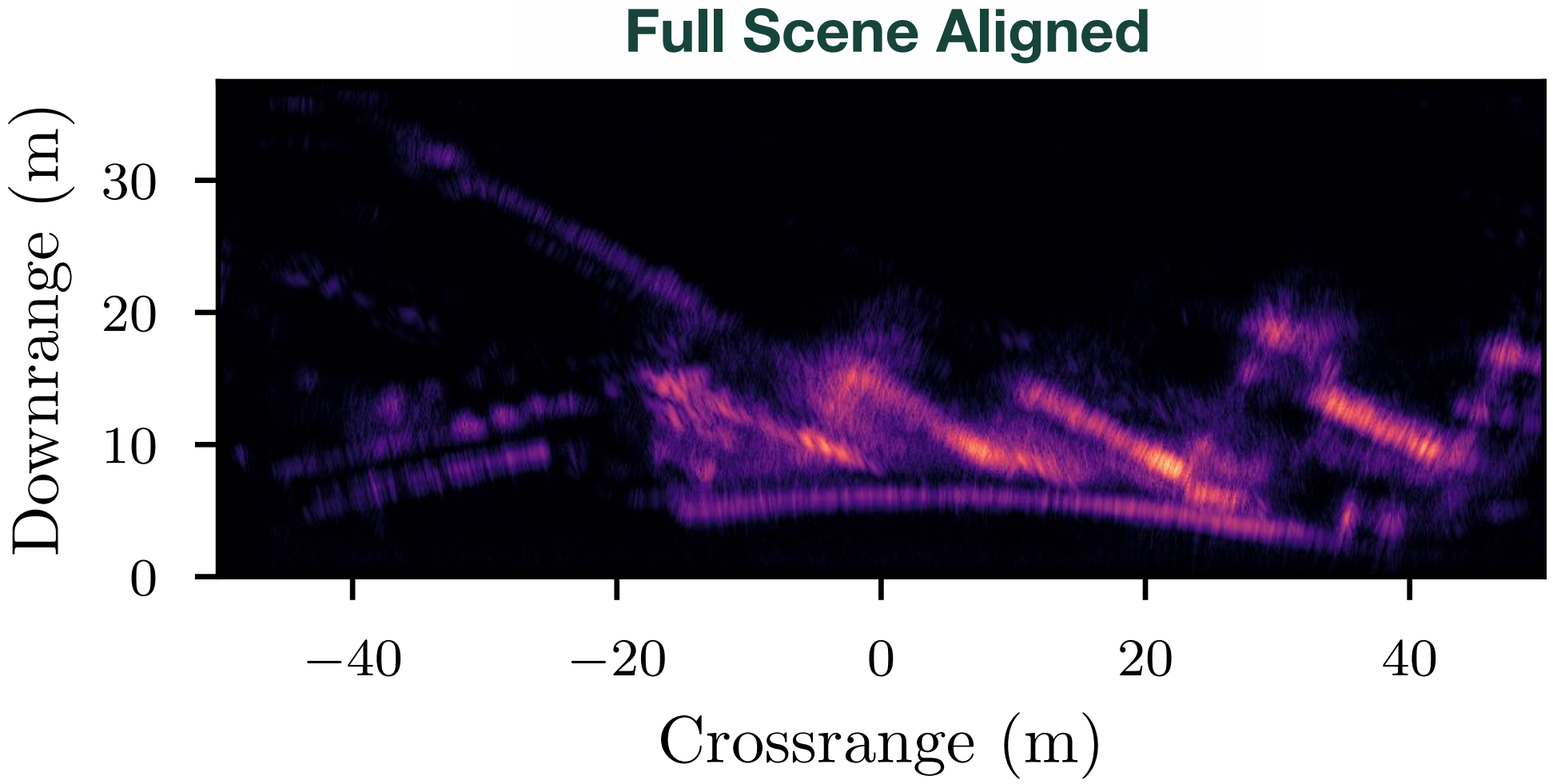
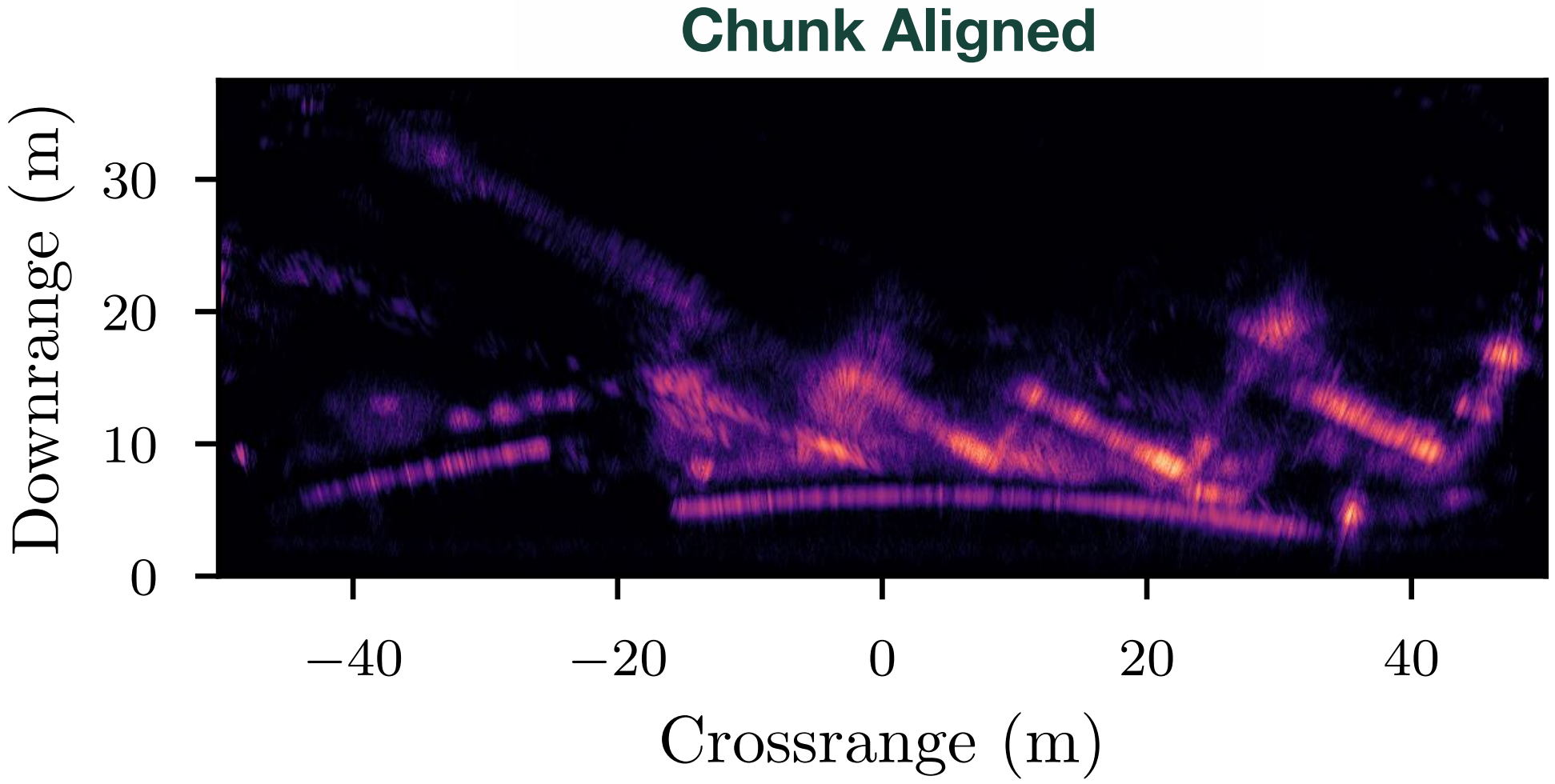


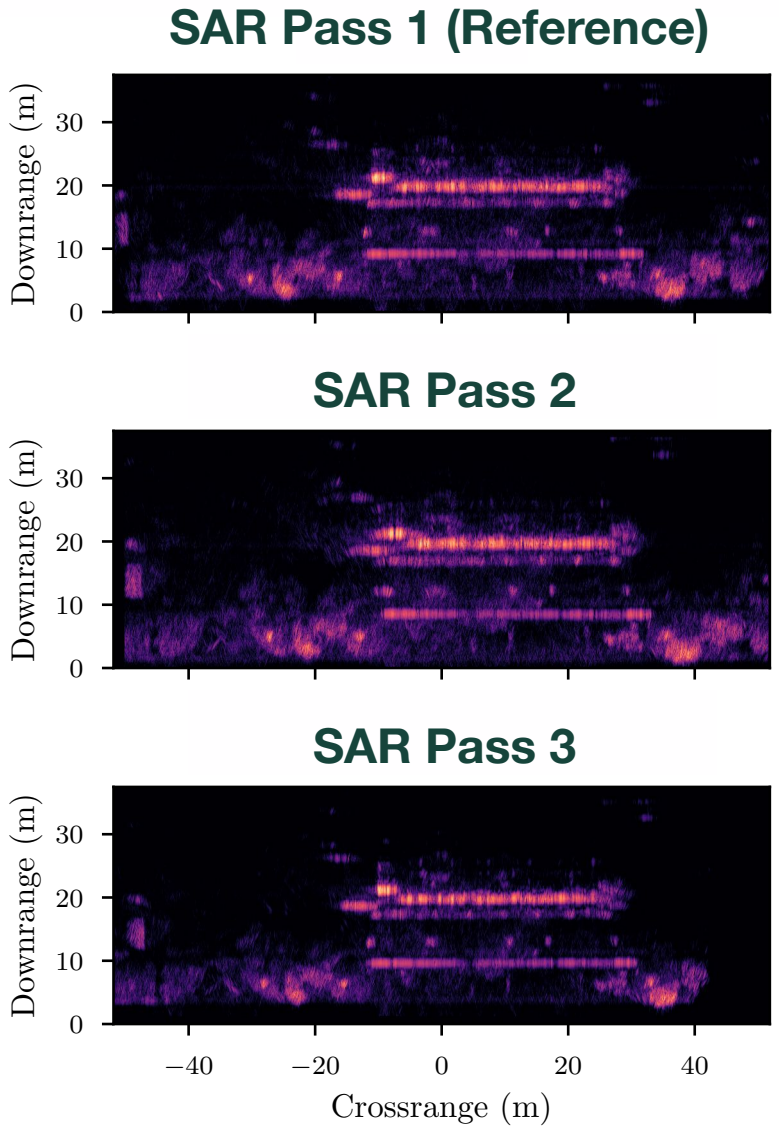
Scene 2 | Three Passes



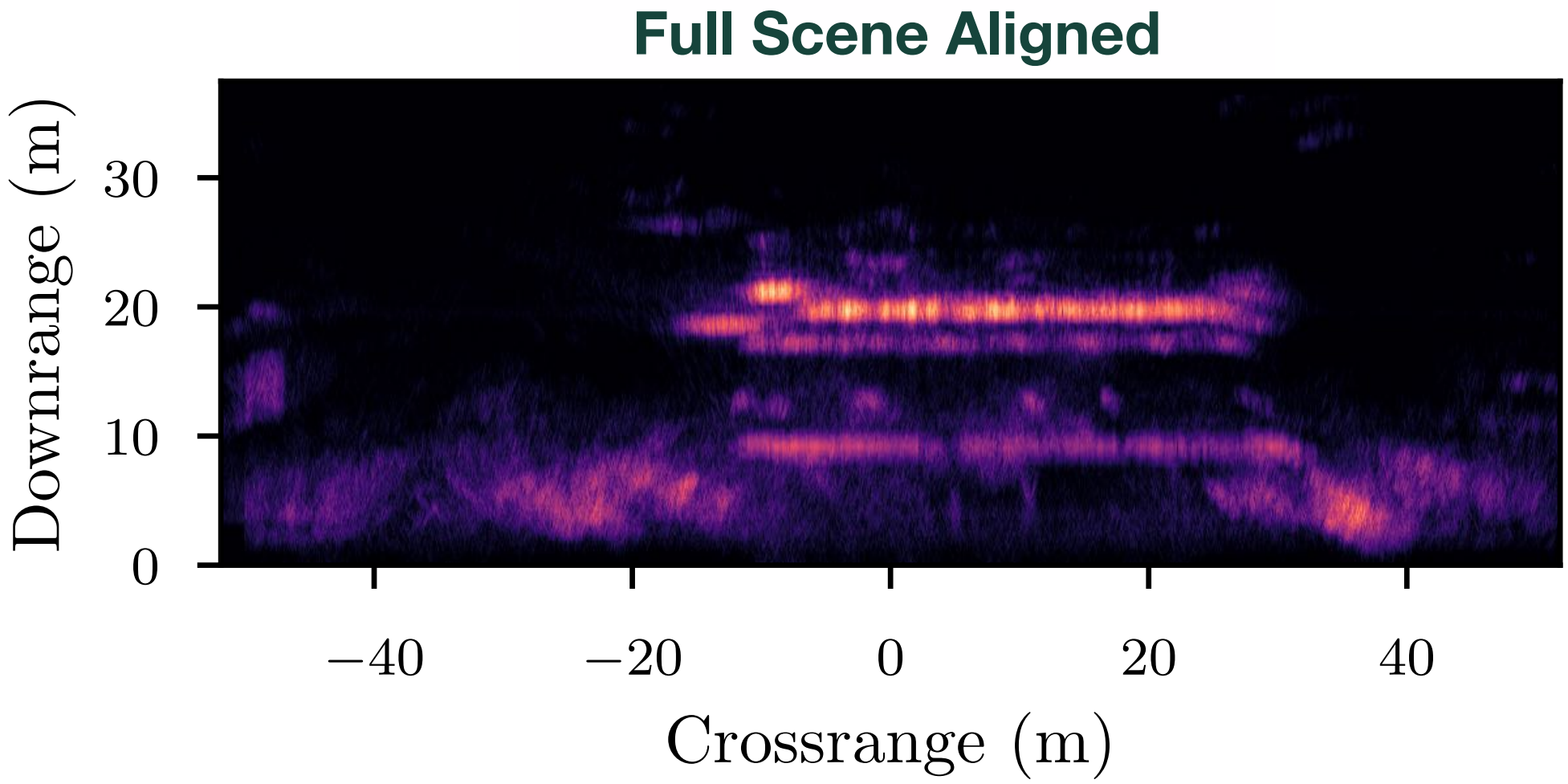
Scene 3 | Three Passes

Spartan Village Autonomous Vehicle Test Facility, Michigan State University

Scene 3 | Three Passes



Scene 3 | Three Passes



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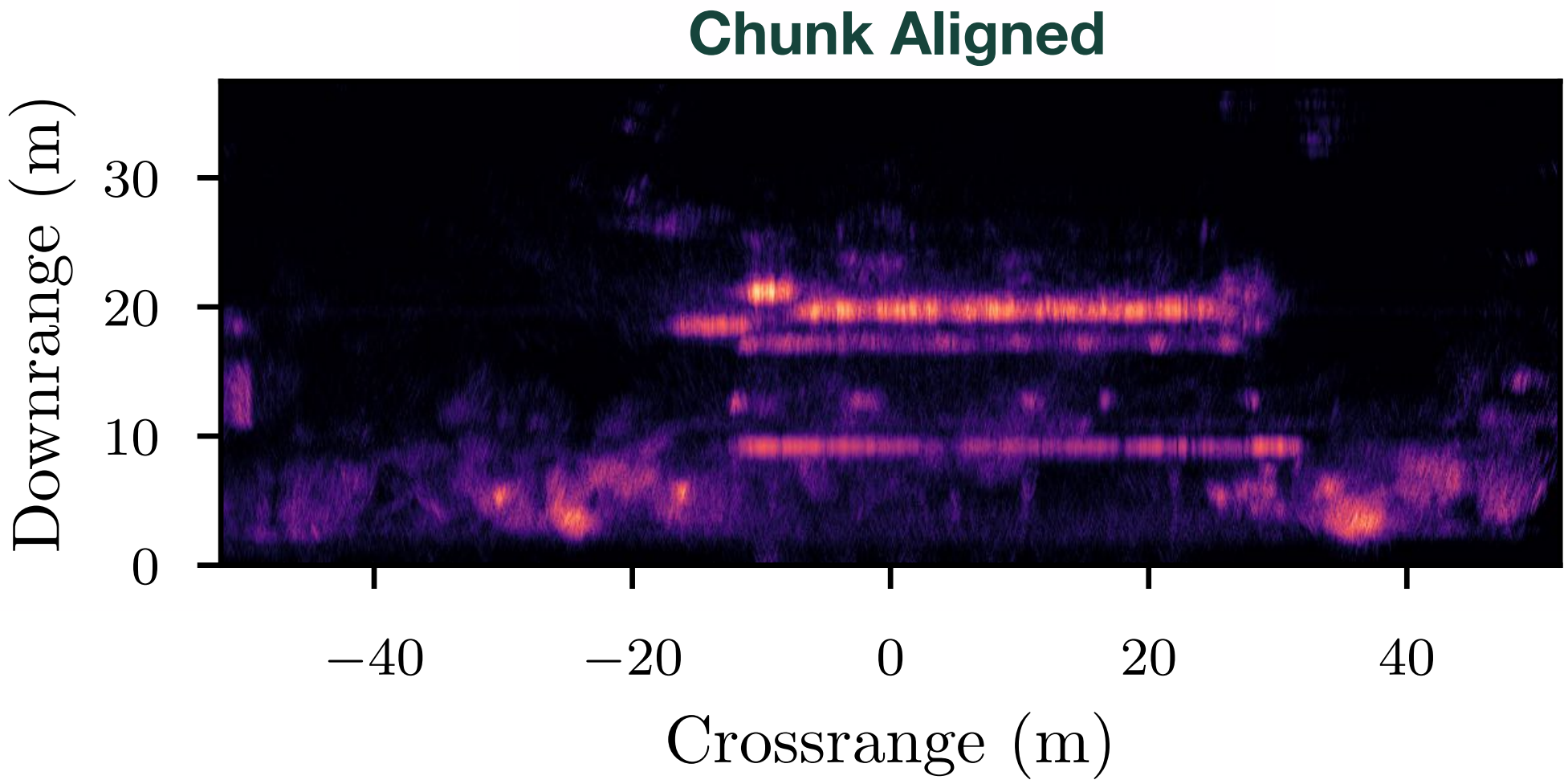


Conclusion

- Proposed a simple technique for **C-band automotive SAR image fusion**
- Utilizes **efficient range migration algorithm** for image formation
- **Compensates for motion distortion** using sub-aperture alignment method
- **Experimentally demonstrated scene fusion** on three scenes in the C-band

Thank You

Contact: merlojas@msu.edu

A | Backup Slides

Platform Motion Model

Assumptions:

- Constant motion
- Stop-and-go approximation

Position Model:

$$x_n = n v_a \tau_\mathrm{p}$$

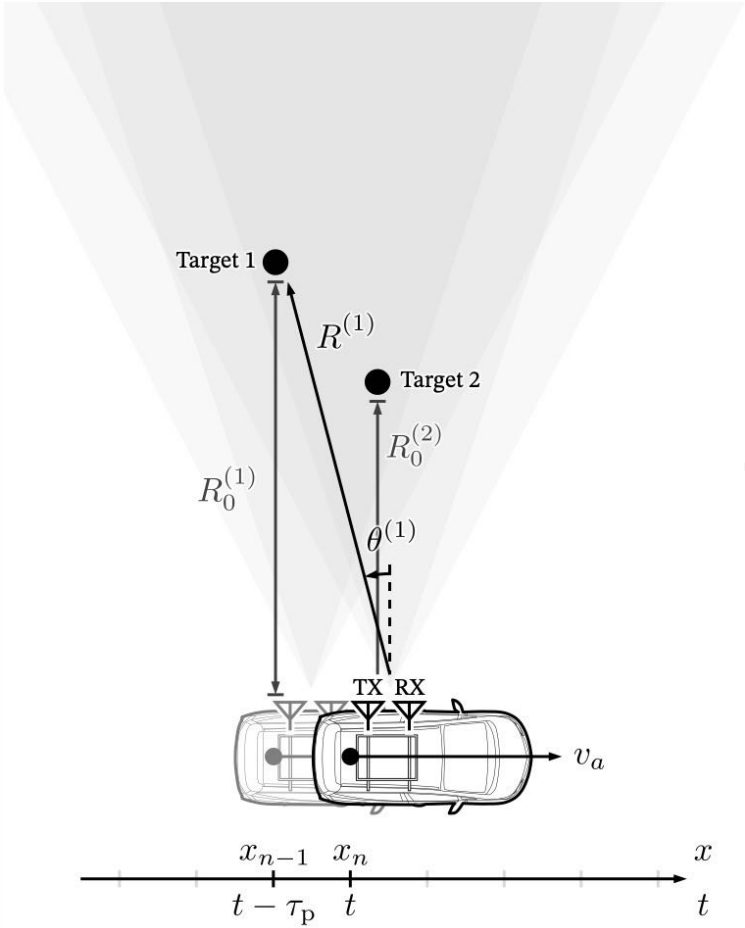
where

n: pulse number

v_a: platform velocity

τ_p: pulse repetition interval

Platform Motion



Target Range vs. Position