Synthetic Aperture Radar Imaging Using a Small Consumer Drone

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Outline

I. Motivation and Objective
II. Drone SAR System
III. Validation on Corner Reflectors
IV. Preliminary Data on Other Targets
V. Conclusion

Motivation

- Small drones have become popular for aerial photography.

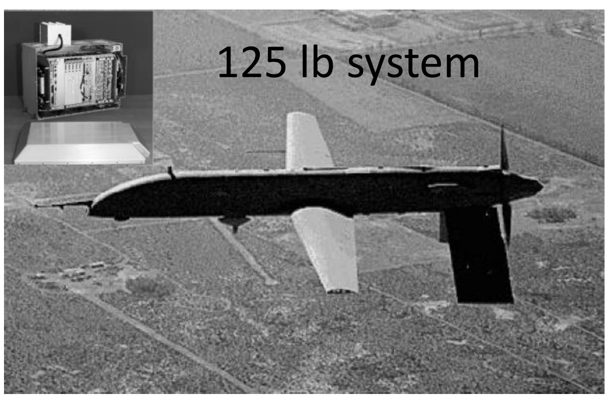
Motivation

- What happens when you mount a radar on the drone?

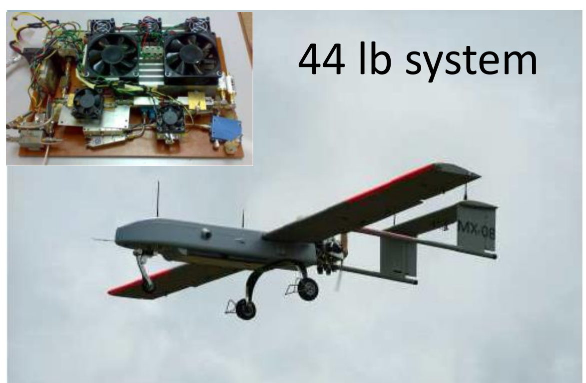
Motivation

- Small drones have become popular for aerial photography.
- Radar imaging could provide complementary information and extended operating conditions.
- Applications in scientific, agricultural, and environmental monitoring.
- UAV-SAR systems exist but are typically too heavy and need to be supported by large UAVs [1-3].

[1] Lynx, Sandia, 2000.



[2] Koo et al., 2012.



[3] NanoSAR, BYU, 2006.

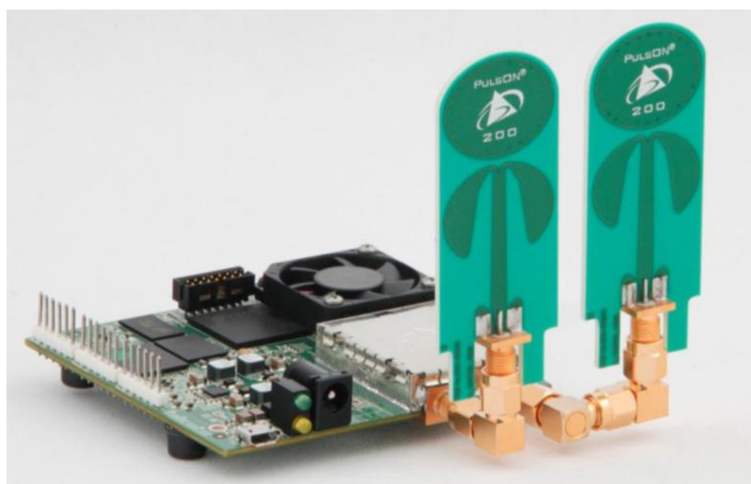
Objective

Develop and demonstrate a low-cost SAR system that is mounted on a small consumer drone (DJI Phantom 2).

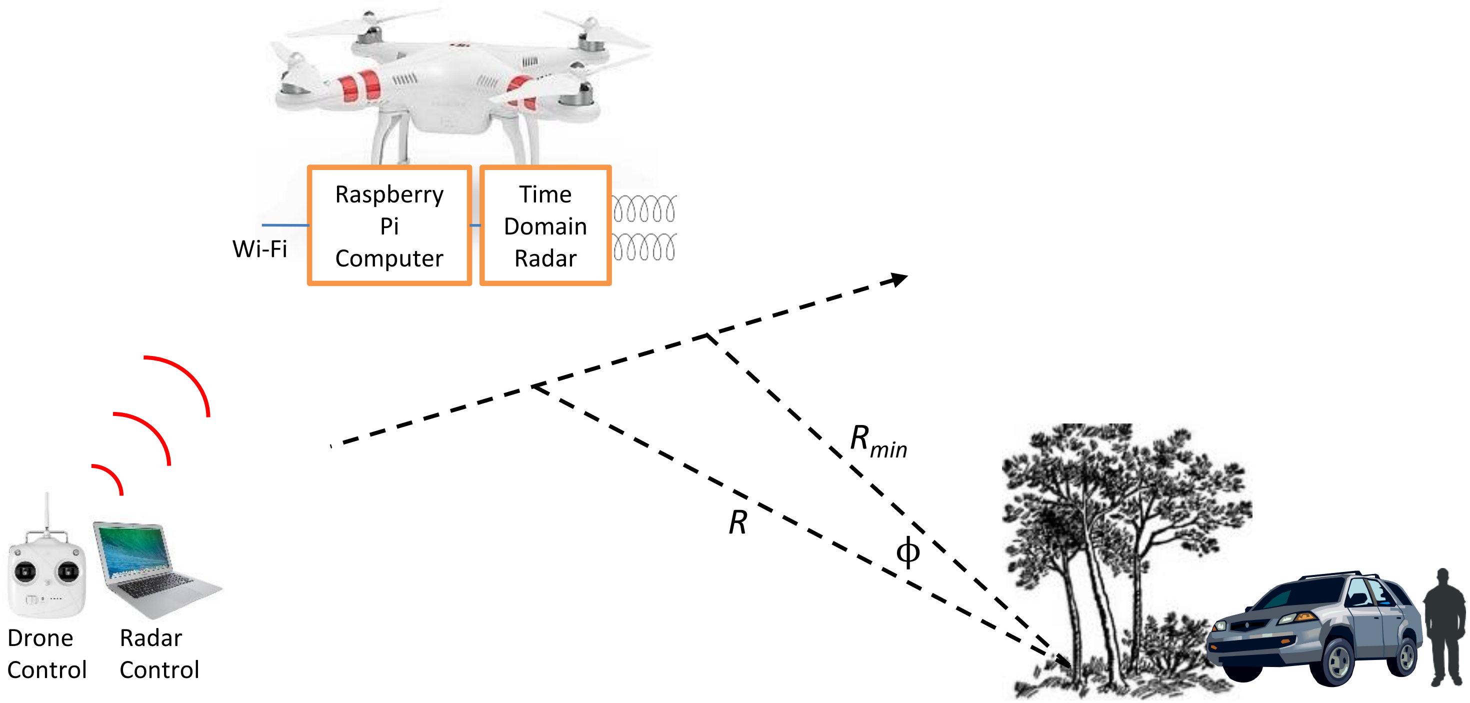
Scientific Question: Can a low-cost, high-resolution SAR system be realized on a small consumer drone (whose maximum payload is typically less than 1 lb)?

PulsON 410 UWB Radar

- PulsON 410 (P410) radar by Time Domain Corporation.
- Board is 7.6 cm x 8 cm x 1.6 cm, weighs 58 grams, and can be battery powered.
- Emits short pulses at a pulse repetition frequency of 10 MHz.
- Equivalent frequency bandwidth from 3.1 to 5.3 GHz centered at 4.3 GHz.
- USB interface to control radar and transfer range profiles.

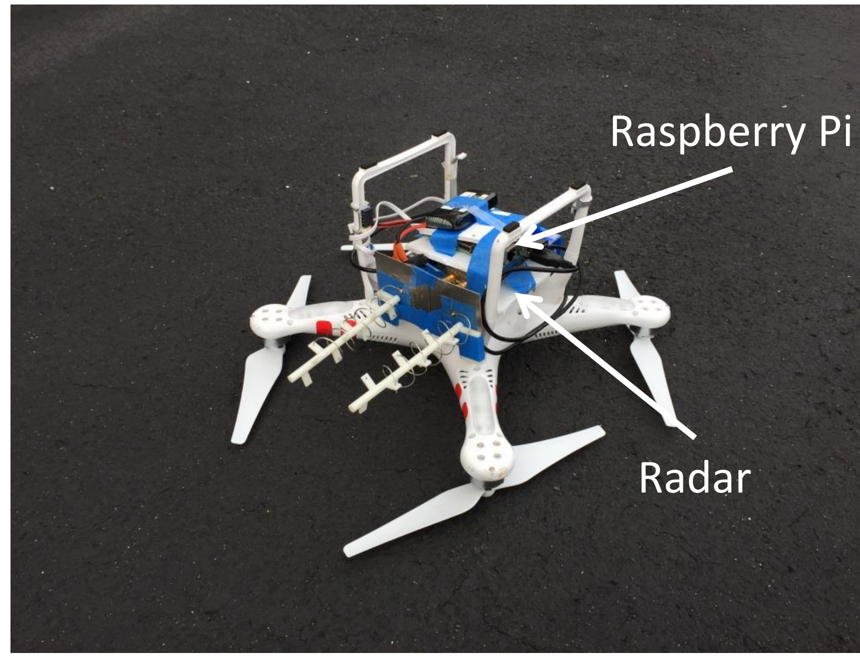


Drone SAR System



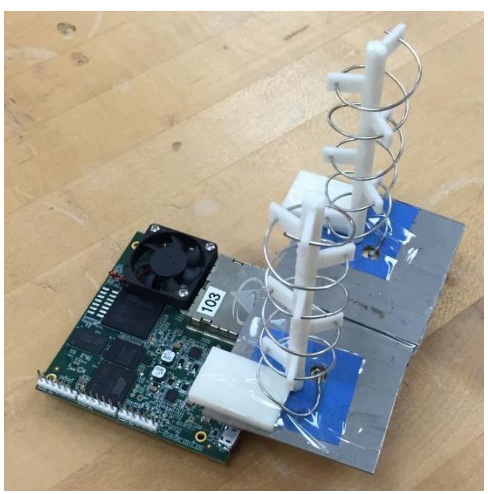
SAR system consists of P410 radar, Raspberry Pi + Wi-Fi Dongle, helix antennas mounted on aluminum ground planes. Entire system (including cables and batteries) weighs less than **300 g**.

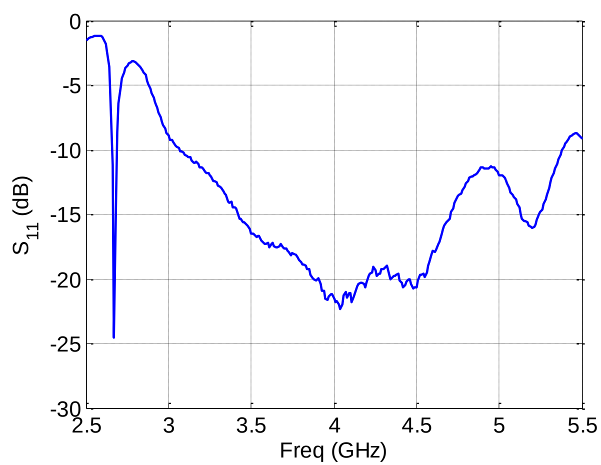
Drone SAR Prototype Photos

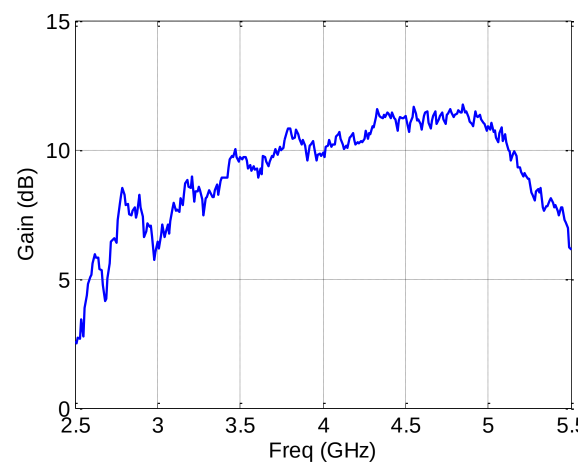


Helix Antennas

- Broadband 5-turn helix antenna centered at 4 GHz.
- Supported by 3-D printed mold.
- Aluminum ground planes.
- 1 right-hand CP for Tx, 1 left-hand CP for Rx.
- Gain: ~ 10 dB ; Two-way 3 dB beamwidth: $\sim 15°$

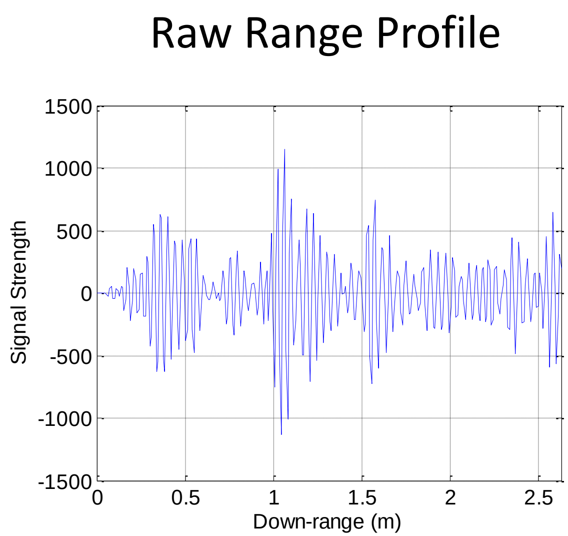


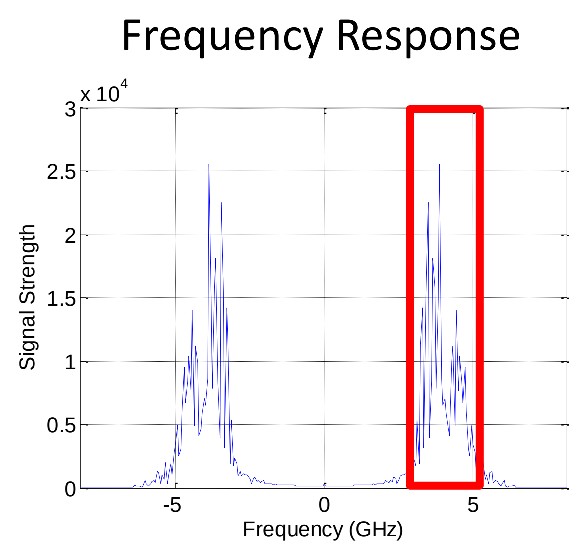




Measurement Range Profiles

- Measured range profiles are real valued but finely sampled in time.
- Use FFT to get the complex frequency response and only keep data from 3.1-5.3 GHz.





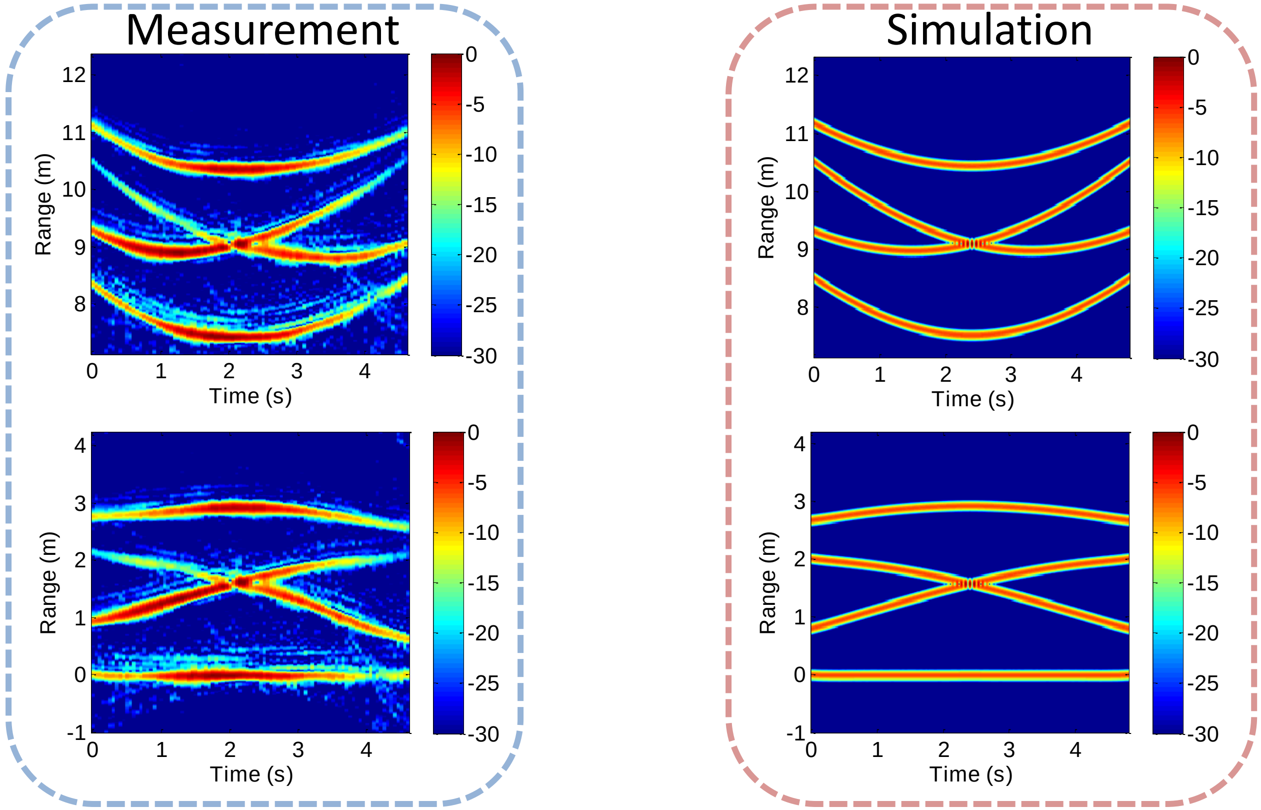
Validation on Corner Reflectors

- 4 small aluminum trihedrals as point-scatterer targets.
- Range profiles collected (at 20 Hz) by flying drone in a straight line across measurement scene.
- Prominent persistent scatterers facilitate range alignment for image formation.

Motion Compensation

Raw Sinogram

Aligned Sinogram



- Range profiles show significant range migration.
- Align to closest scatterer.
- Good agreement with point-scatterer simulation.

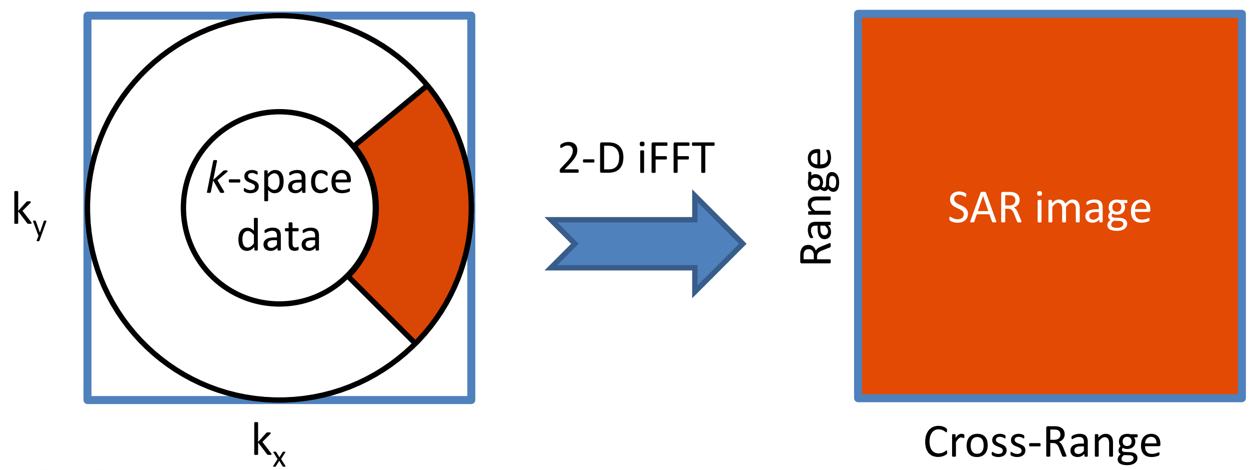
Image Formation

- Frequency/angle data are placed in *k*-space.

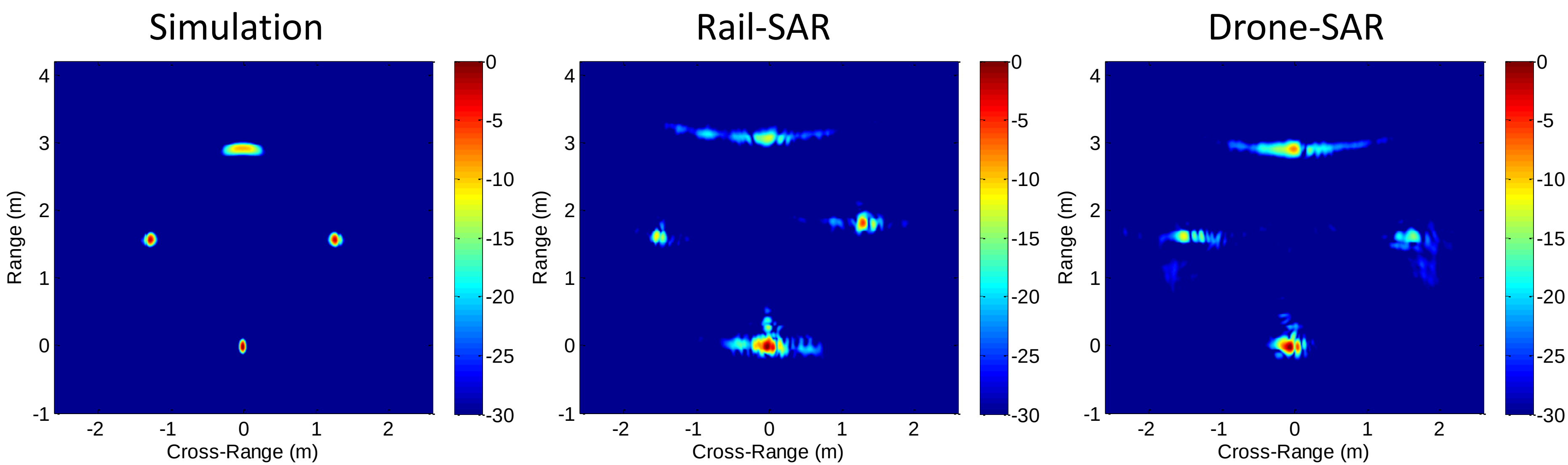
$$Image(r, cr) = \iint E^s(f, \phi)\, e^{jk_x r} e^{jk_y cr} dk_x dk_y$$

$$where \begin{cases} k_x = \dfrac{4\pi f}{c}\cos\phi \\ k_y = \dfrac{4\pi f}{c}\sin\phi \end{cases} \quad ; \quad \phi = \cos^{-1}\left(\frac{R_{min}}{R}\right)$$

- Polar reformat to uniform k_x-k_y space and take 2-D inverse fast Fourier transform to obtain image.

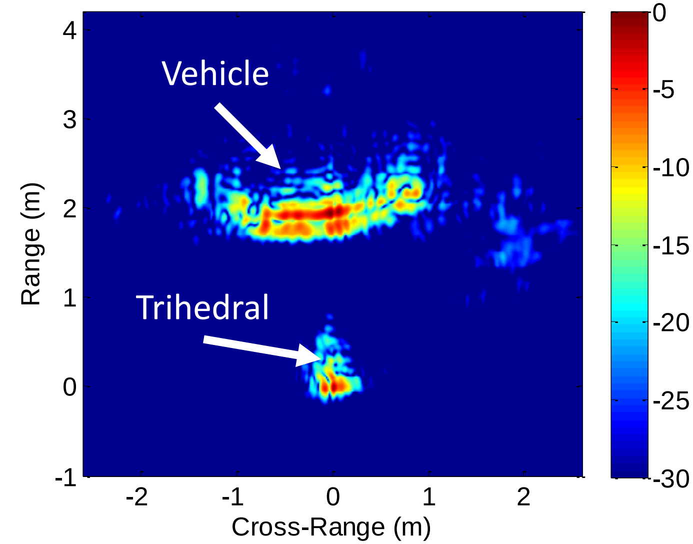


Resulting SAR Images



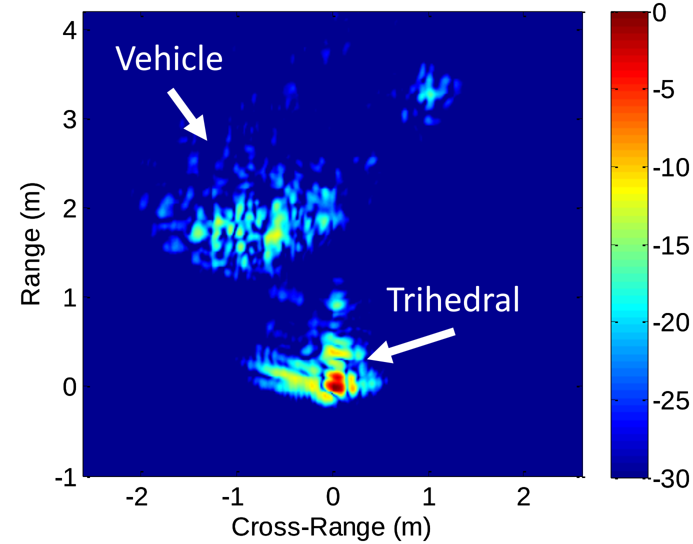
- 3 focused scatterers. Cross-range smearing of farthest scatterer due to near-field effects.
- Good agreement between simulation and rail-SAR.
- More blurred result in drone-SAR.

Application to Other Targets



- Trihedral is left in the scene for reference.
- Stationary vehicle and human targets.
- Able to generate SAR images of other targets.

Application to Other Targets



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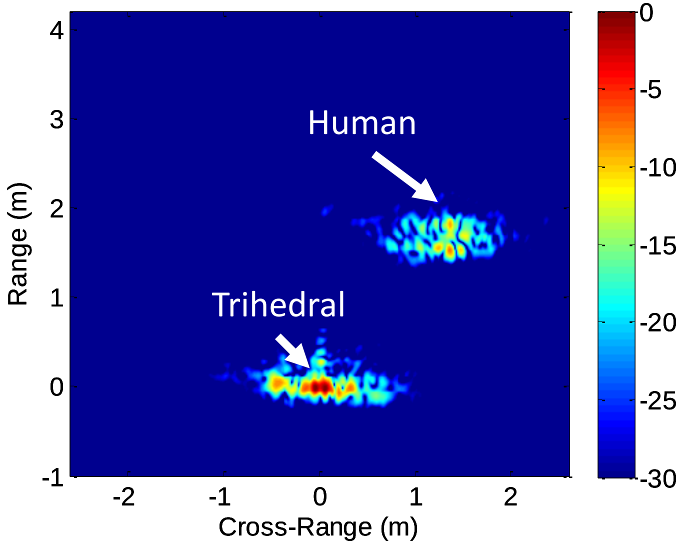


- Trihedral is left in the scene for reference.
- Stationary vehicle and human targets.
- Able to generate SAR images of other targets.

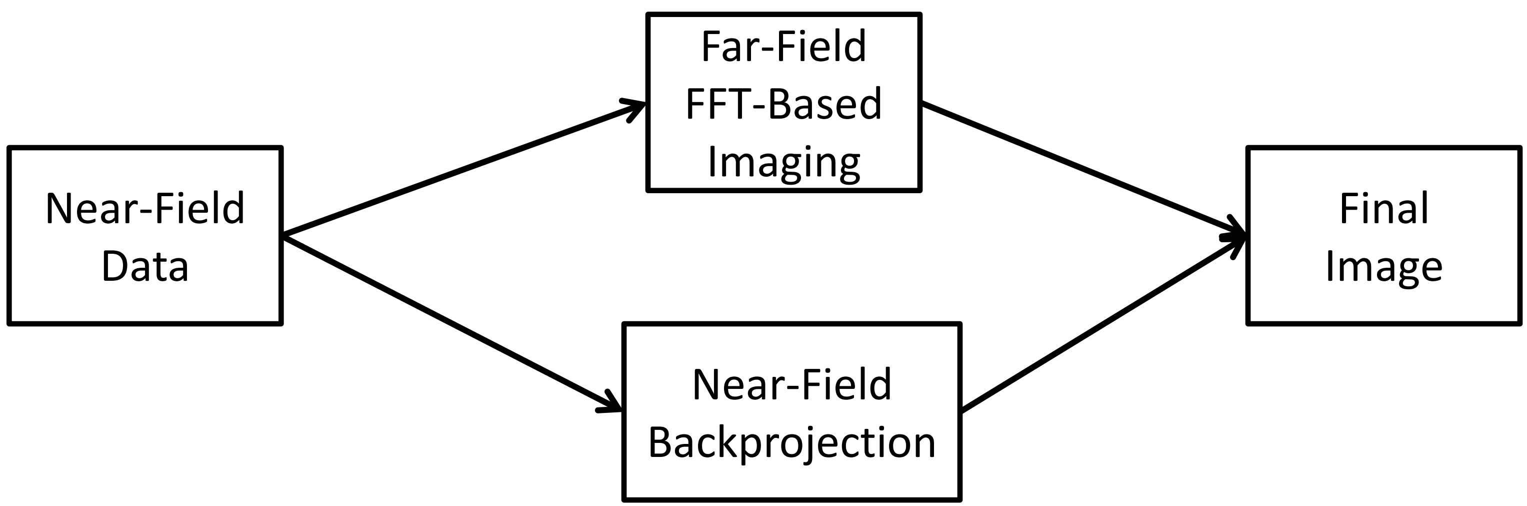
Recap

- Devised a portable, lightweight SAR system that can be mounted on a small drone.
- Verified its imaging capability on trihedrals and then collected preliminary data of other targets.

- Current work.
  - Near-field correction
  - Downward-looking SAR

Near-Field Effect Correction

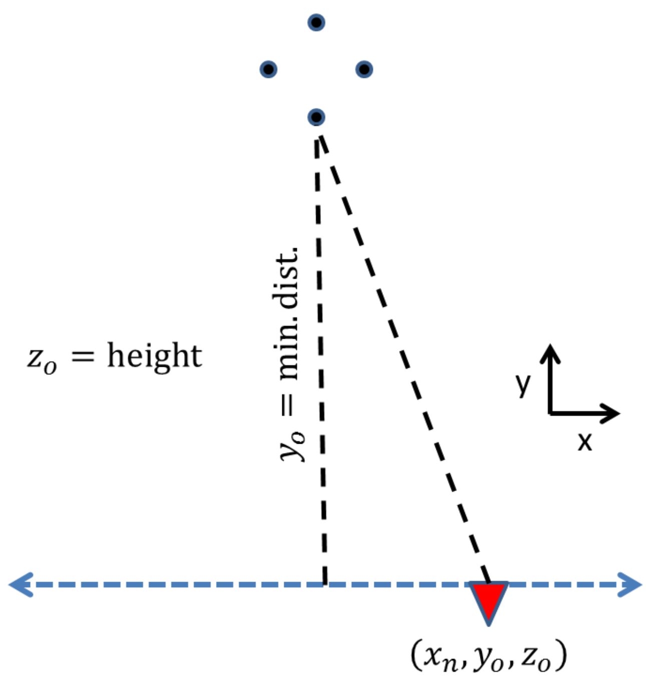
- Previous: used far-field FFT-based imaging scheme on near-field data.
- Solution: apply near-field backprojection imaging scheme.

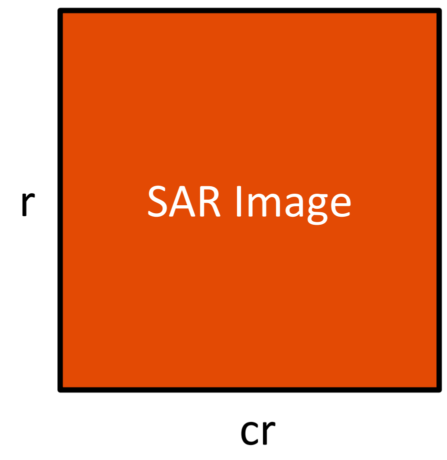


Near-Field Backprojection

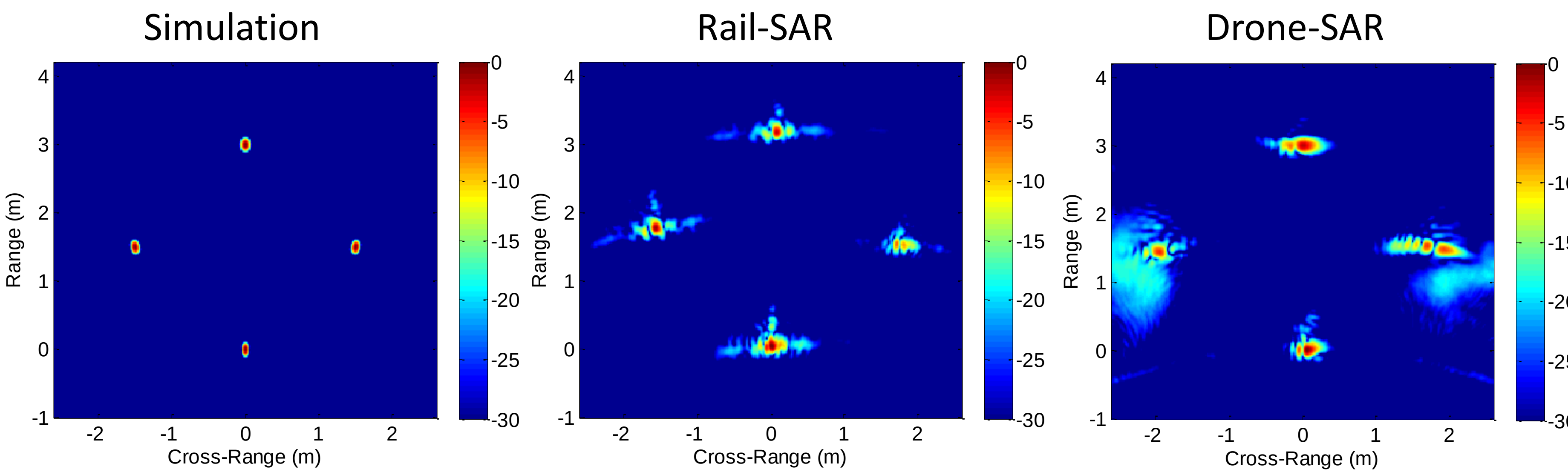
- Matched filter algorithm that projects the scattered field data into the phase function.

$$\mathrm{SAR}(r, cr) = \frac{1}{NM} \sum_{n=1}^{N} \sum_{m=1}^{M} E_s(x_n, f_m) \times e^{j\frac{4\pi f_m}{c}\sqrt{(cr - x_n)^2 + (r + y_o)^2 + z_o^2}}$$



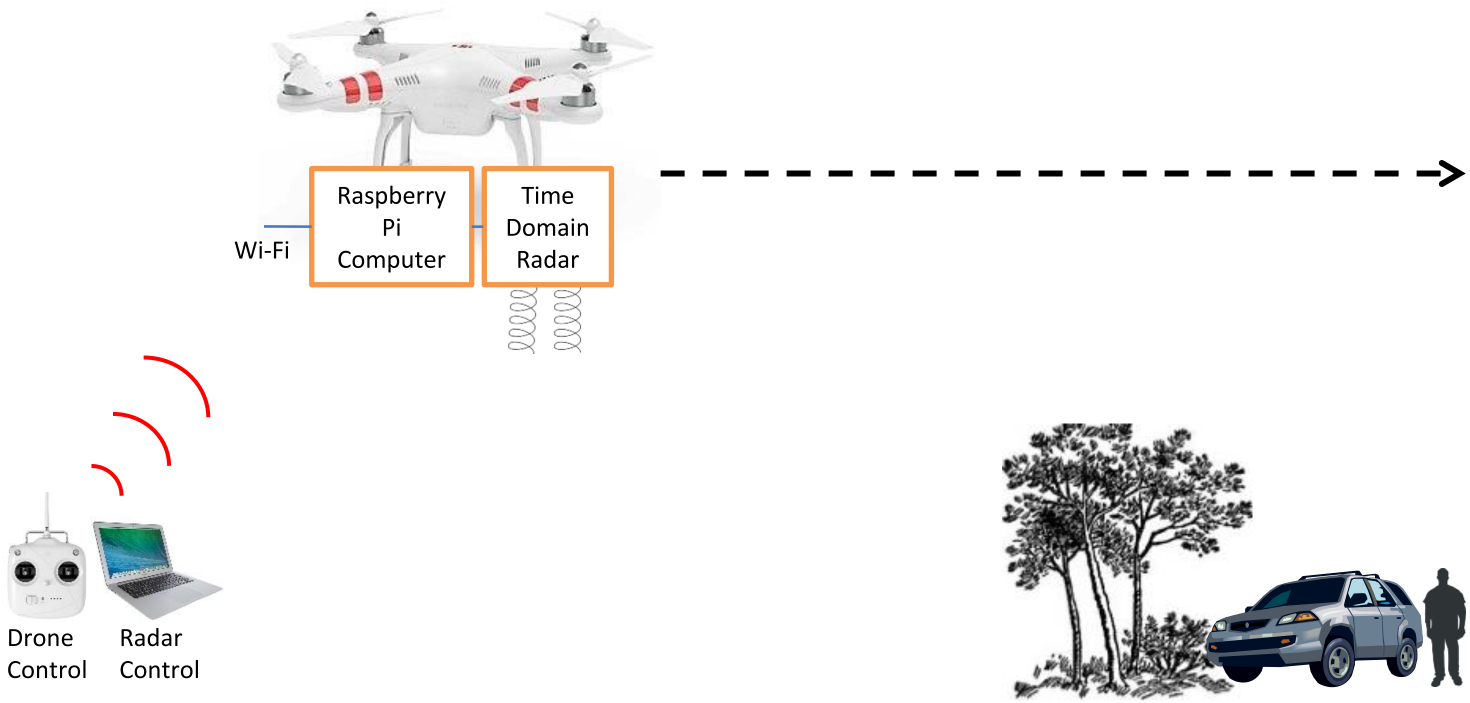


Resulting SAR Images



- Near-field effects have been removed.
- Good agreement between rail-SAR and simulation.
- More blurred result in drone-SAR.

Downward-Looking SAR

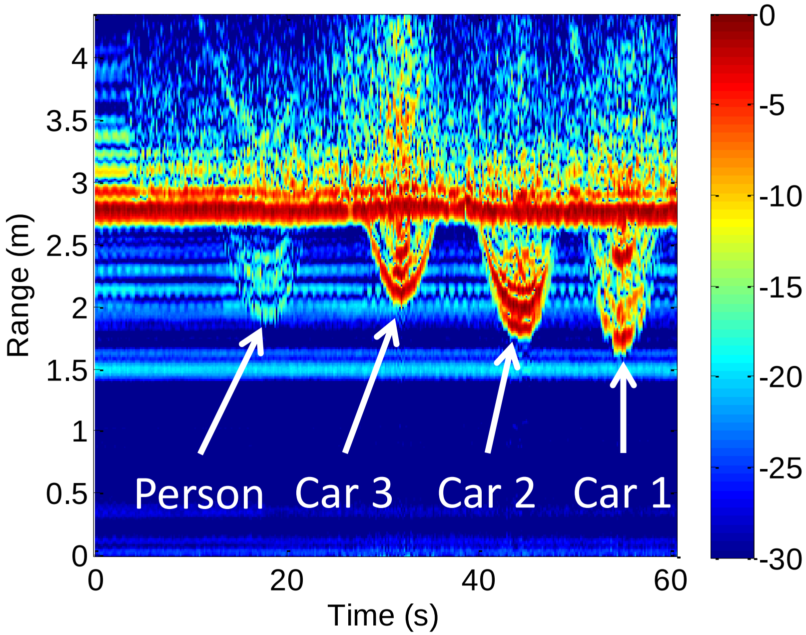


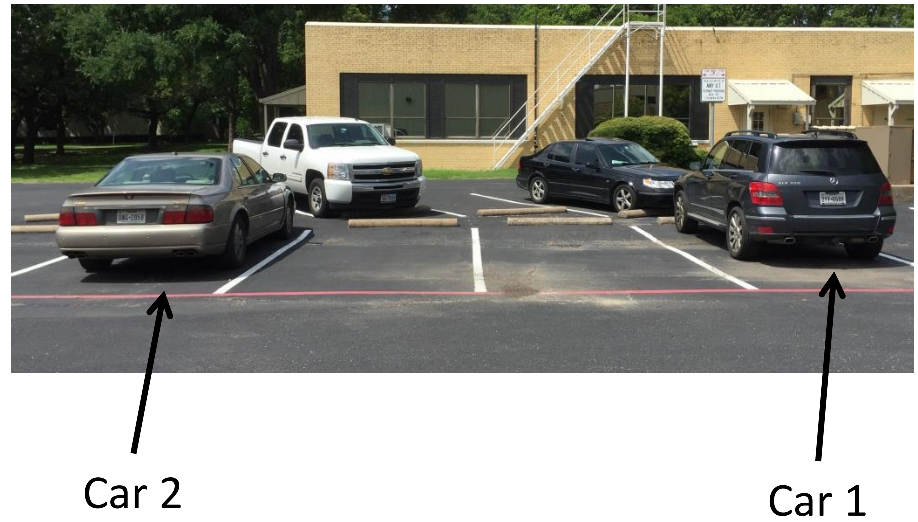
Point antennas at the ground in order to change imaging plane.

Preliminary Investigation

- Currently mounted on a vehicle for preliminary investigation.
- Attached drone-SAR system on extension pole and pointed downward.
- Drive across parking lot and collect range profiles.

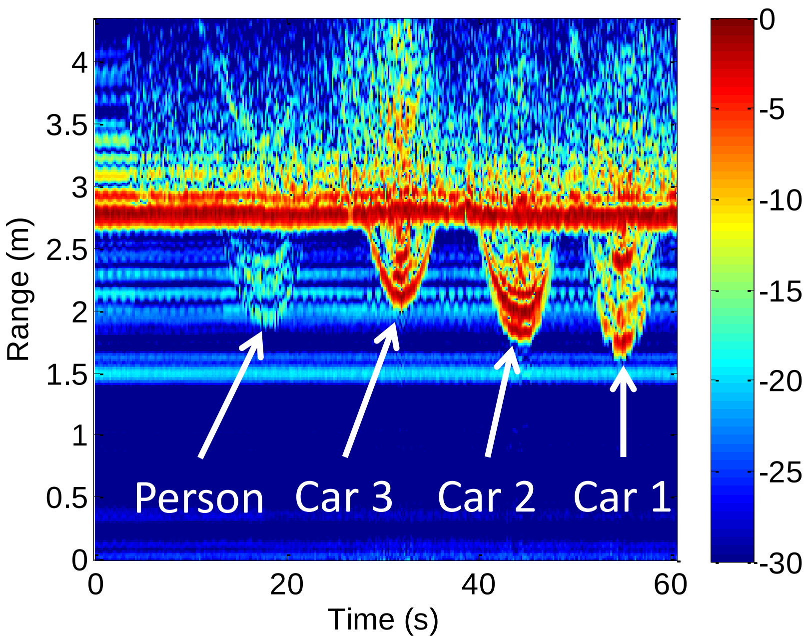
Resulting Range Profiles

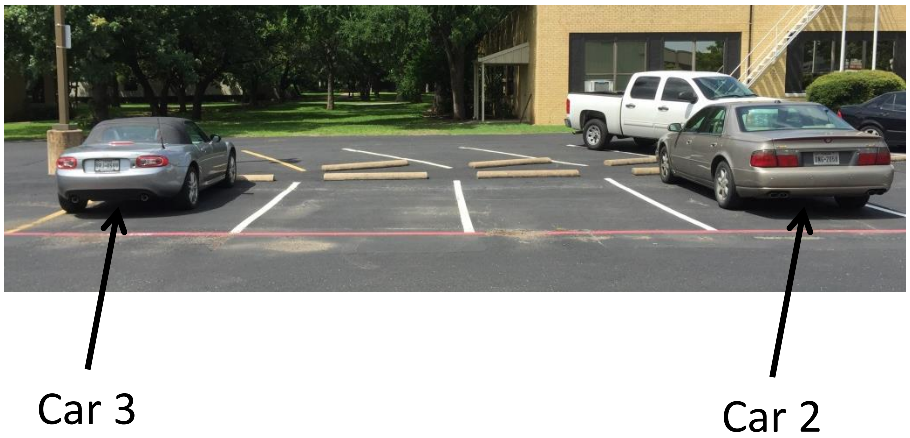




- Strong ground bounce and minor residual platform returns.
- Height information is captured.
- Multiple scattering is visible.

Resulting Range Profiles





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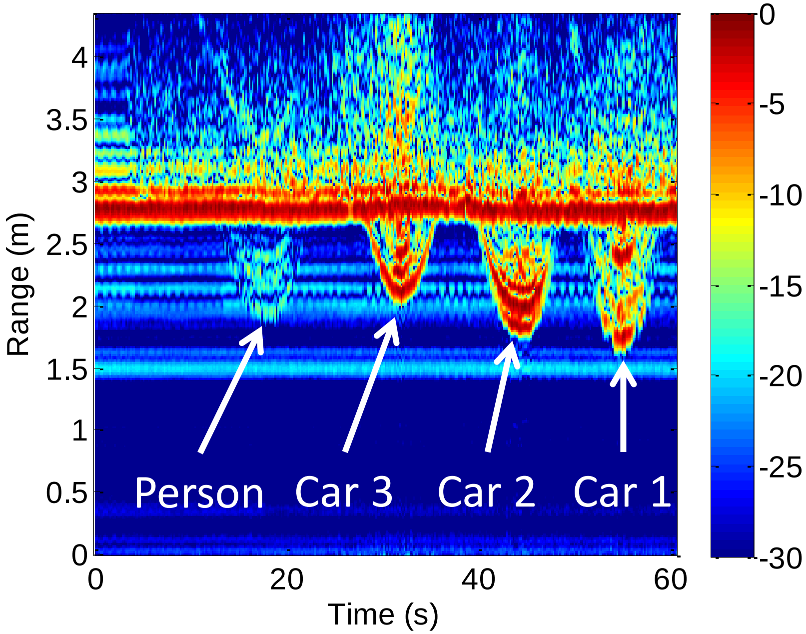

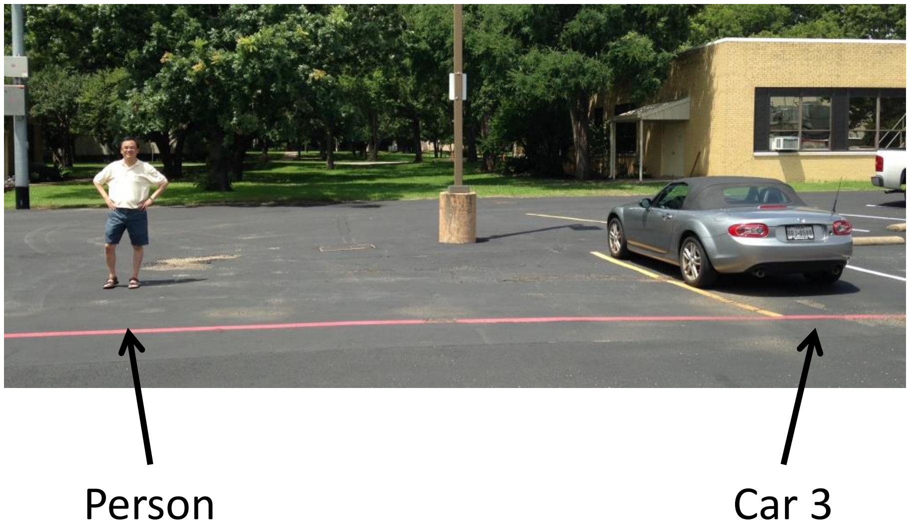

- Strong ground bounce and minor residual platform returns.
- Height information is captured.
- Multiple scattering is visible.

Conclusion

- Devised and demonstrated a portable, lightweight SAR system that can be mounted on a small drone.
- Pros:
  + Low-cost and portability opens up many new possibilities for in-situ measurements that were prohibitive in the past.
- Cons:
  – Needs prominent scatterer (absence of navigation data).
  – Drone flight instability.

Future Work

- Continue downward-looking SAR for frontal view imaging of targets.
- Examine radar signatures under co-polarized and cross-polarized scenarios.
- SAR imagery of targets through optical obstructions (smoke, foliage).
- Blind motion compensation / obtain navigation data.

Acknowledgments

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