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Radar Signatures of Small Consumer Drones

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Motivation and Objective

- The proliferation of small consumer drones has raised much recent interest in their regulation and monitoring.
- One potential way to detect and identify these drones is using a ground-based radar.
- **Objective:** To investigate the radar signatures of these small drones.

DJI Phantom

3DR Solo

DJI Inspire

Approach

- Carry out laboratory measurement of small consumer drones.
- Examine their radar signatures in the form of inverse synthetic aperture radar (ISAR) images.
- ISAR imaging provides not only radar cross section (RCS), but also maps the dominant scattering in 2-D.

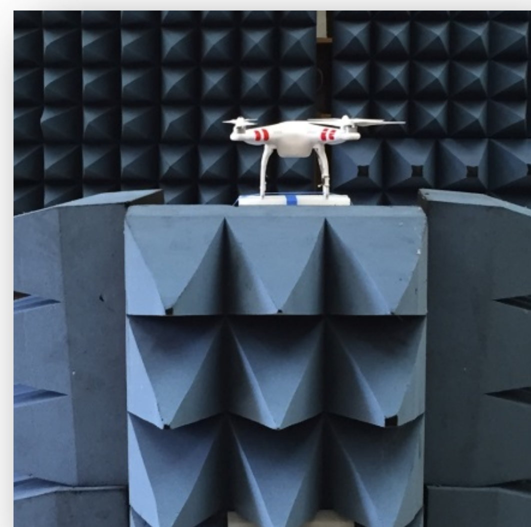
Scientific Questions:

1. Will the small size and low reflectivity of the drone body result in a very low RCS?
2. Will the spinning propeller blades result in significant Doppler artifacts [1]?

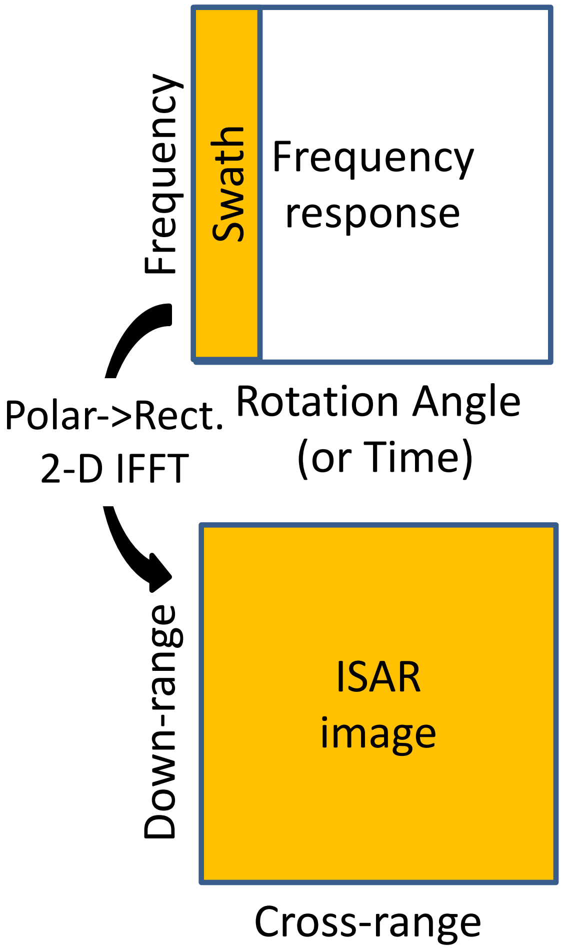
[1] P. Pouliguen *et al.*, *IEEE Trans. Antennas Propagat.*, 2002.

Laboratory Measurement Setup

- Vector network analyzer (VNA) S_{11} measurement.
- Drone mounted and rotated on a turntable.
- Start with baseline scenario and then deviate.
- Calibrated results in terms of absolute RCS using a calibration sphere.
- Horn mismatch and room clutter are reduced by subtracting the moving average.
- 3 GHz of bandwidth.
  - 5 cm of down-range resolution.



ISAR Image Formation



- 2-D image generated using 2-D inverse Fourier transform of frequency/angle data.

$$Image(r, cr) = \frac{1}{K_x K_y} \iint E^s(f, \phi)\, e^{jk_x r} e^{jk_y cr} dk_x dk_y$$

$$where \begin{cases} k_x = \dfrac{4\pi f}{c} \cos\phi \\ k_y = \dfrac{4\pi f}{c} \sin\phi \end{cases}$$

- Angular swath chosen for equal down-range / cross-range resolution of 5 cm.
- Slide swath along angle to generate an ISAR movie.

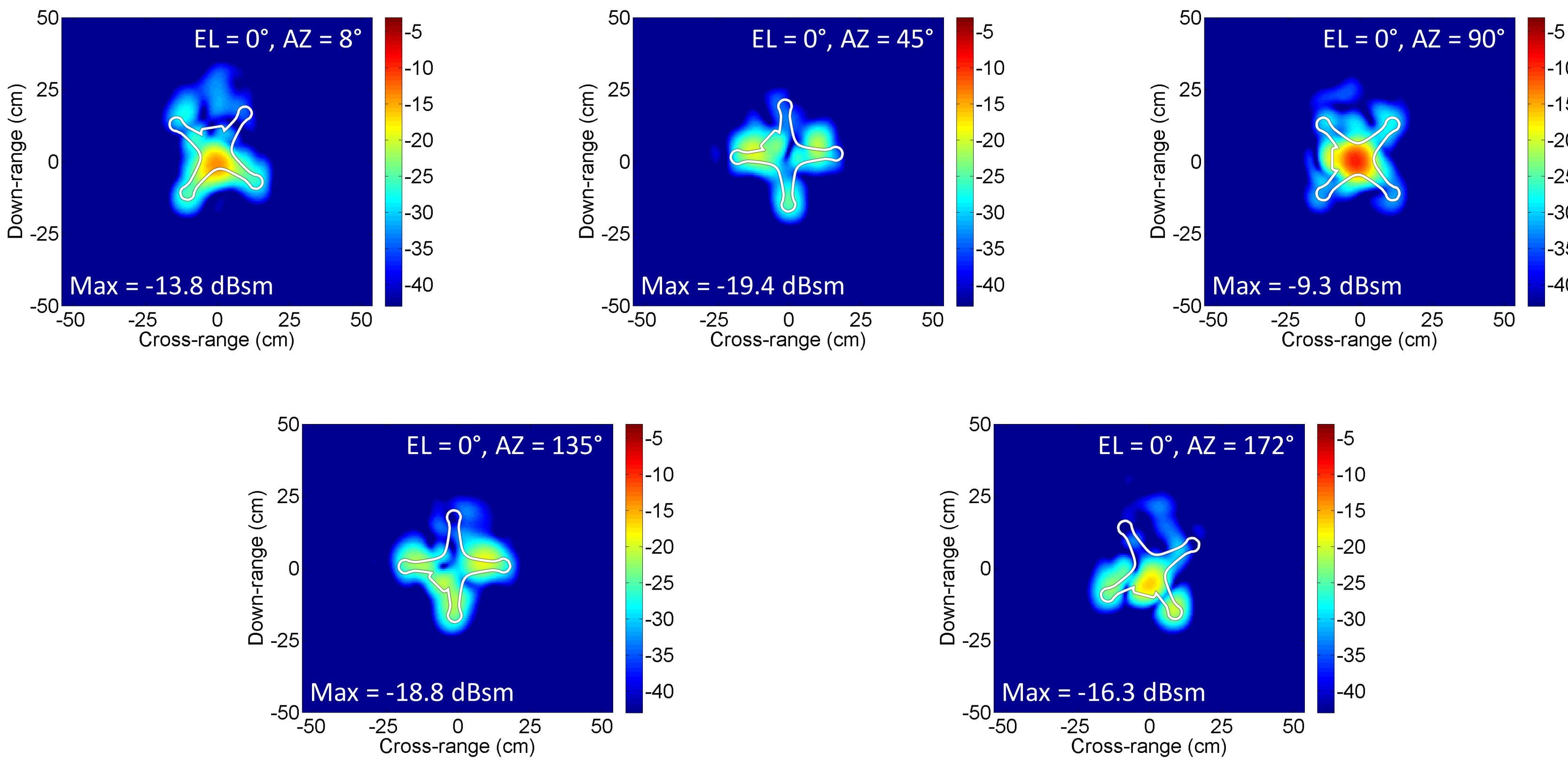
Baseline Scenario

- DJI Phantom 2 (35 cm diagonal).
- Azimuth scan at zero-elevation angle: results in a top-view of the drone.
- 12-15 GHz, blades stationary, VV-pol, no camera.

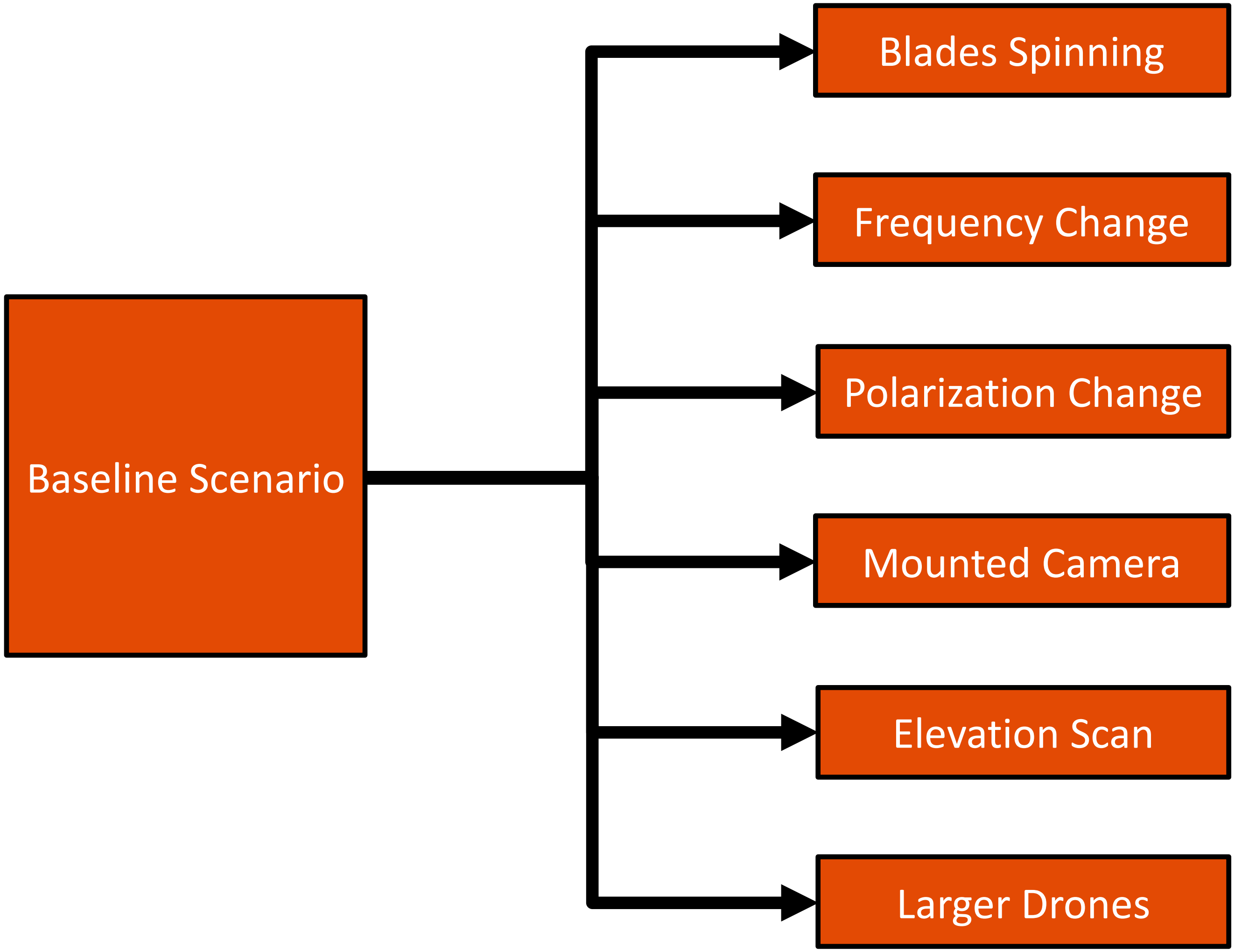
ISAR movie available at: http://users.ece.utexas.edu/~ling/DroneISARMovie.gif

ISAR Snapshots

- ISAR image snapshots at different look angles with an outline of drone overlaid.
- Maximum RCS in each snapshot is listed.



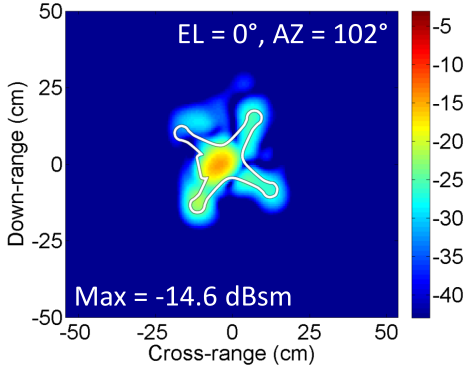
Deviations From Baseline



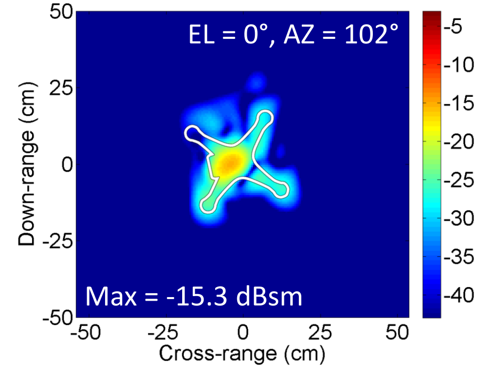
Deviations From Baseline

Rotating Blades

Blades Stationary



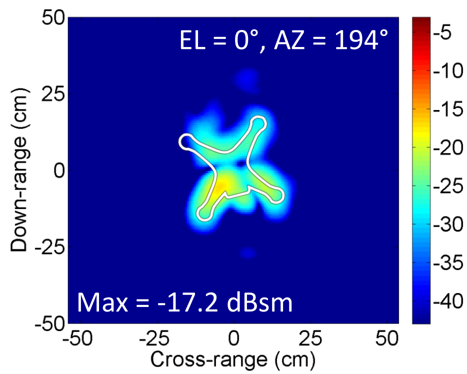
Blades Spinning



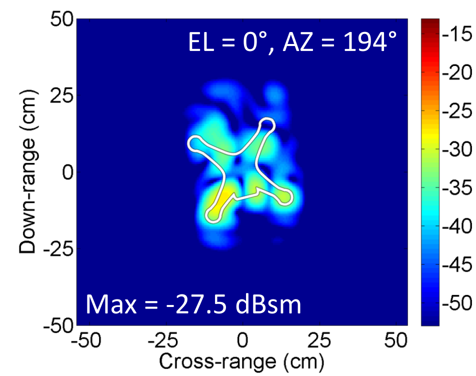
- No significant differences between blades rotating and stationary.

Frequency Change

12-15 GHz



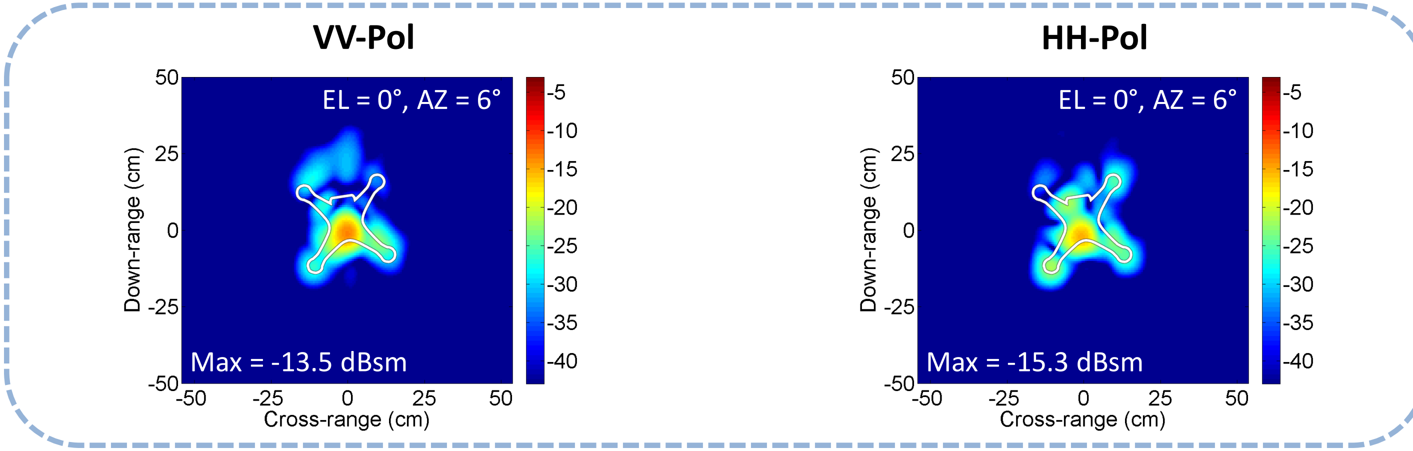
3-6 GHz



- On average, RCS at 3-6 GHz about ~12 dB lower than 12-15 GHz.

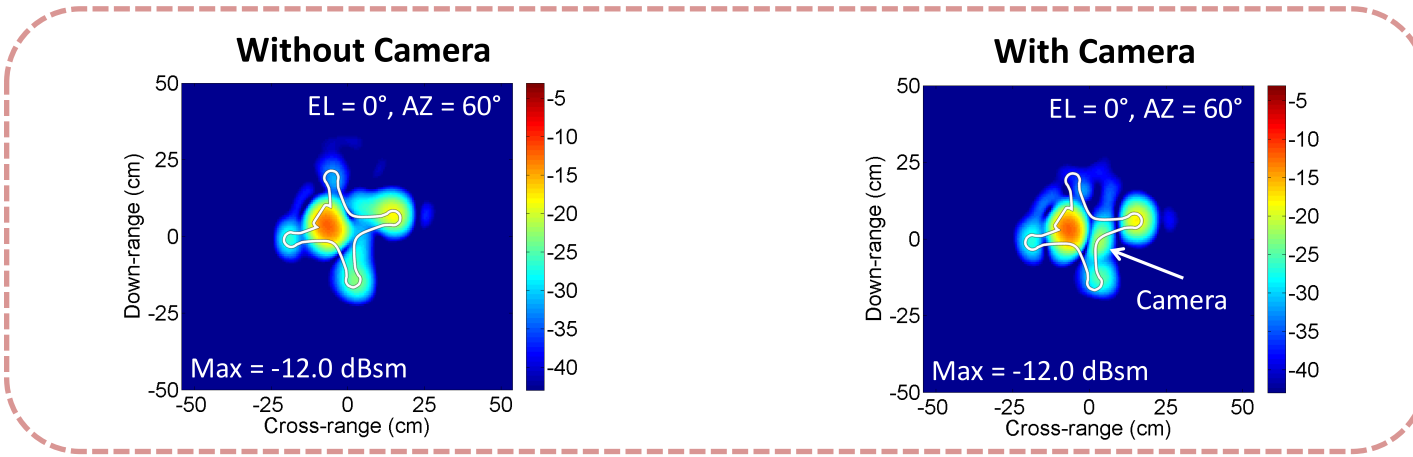
Deviations From Baseline

Polarization Change



- HH-Pol: weaker battery return, stronger motor return.

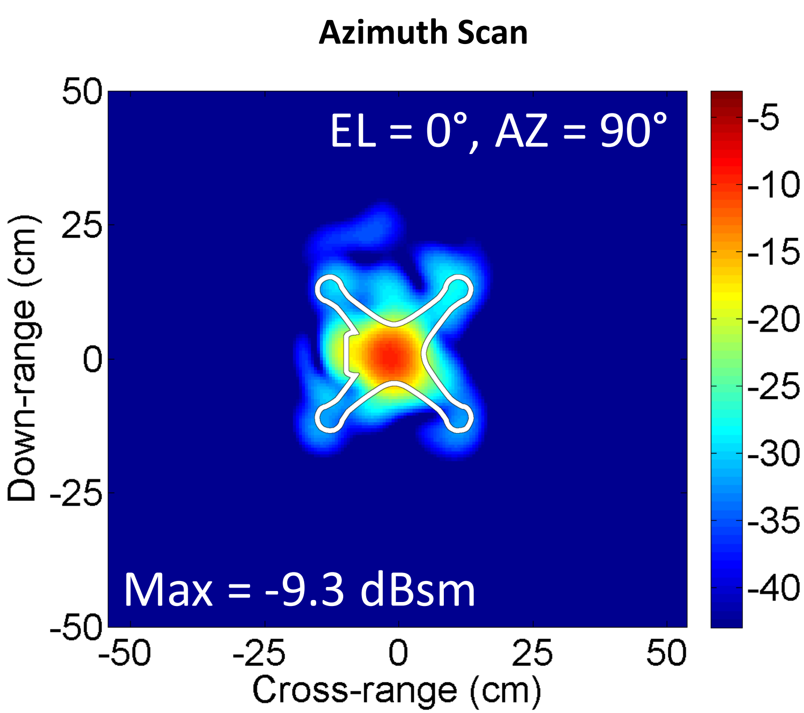
Camera Mounted

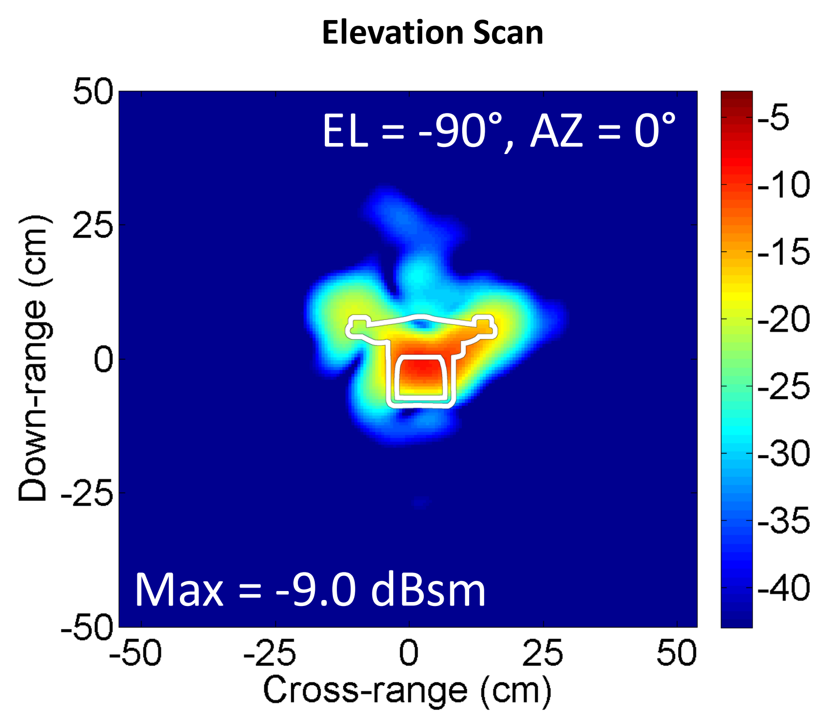


- Camera can only be seen at specific look angles.

Deviations From Baseline

- Elevation scan instead of azimuth scan.
- Captures the shape of the drone in another imaging plane.
- Instead of top-view of the drone, captured the side-view.
- In practice, collected by flipping drone on its side and rotating.



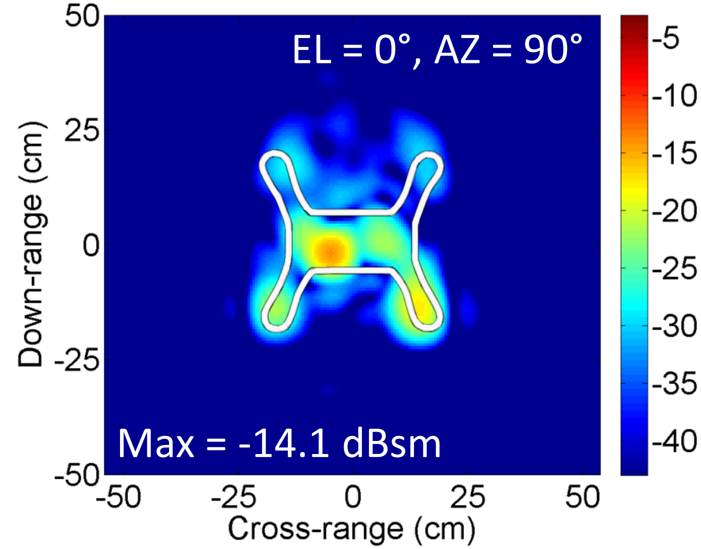


Larger Drones: 3DR Solo

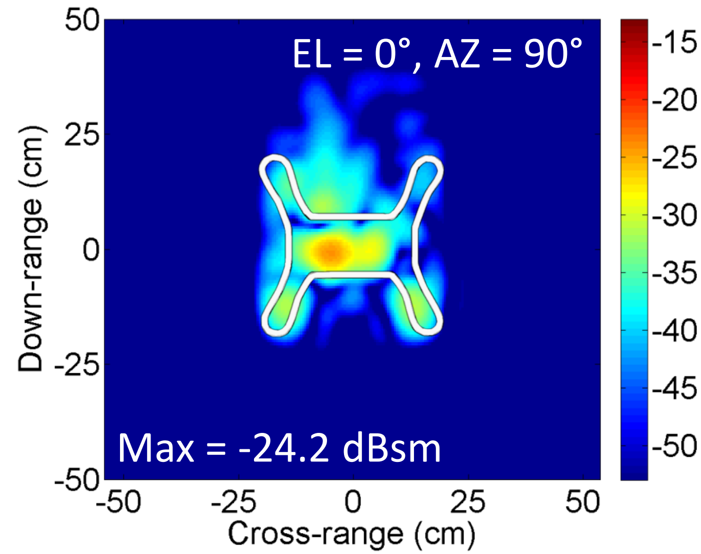
3DR Solo (46 cm diagonal)

- Drone shape and size captured.
- Maximum RCS smaller than Phantom 2 due to body shape.
- Similar trends as Phantom 2.

12-15 GHz



3-6 GHz

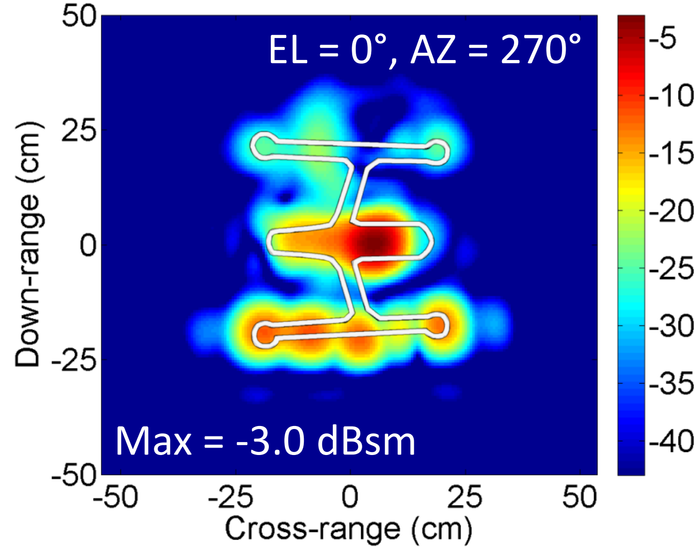


Larger Drones: DJI Inspire 1

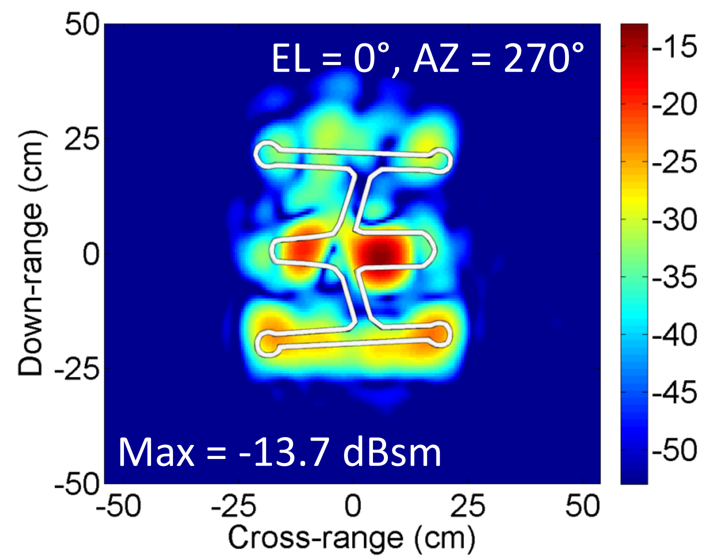
DJI Inspire 1 (56 cm diagonal)

- Drone shape and size captured.
- Additional feature from the horizontal frame.
- Highest maximum RCS of the three drones.
- Similar trends as Phantom 2 and 3DR Solo.

12-15 GHz



3-6 GHz



Recap

- Overall RCS level is low, but the drone size and shape can be captured in the ISAR imagery.
- Non-plastic portions dominate their radar signatures (such as motors, battery pack, and carbon-fiber frame).
- Drone propellers did not contribute a significant return relative to the drone body (static or spinning).
- Data collection was under idealized conditions, but it should be feasible to collect such data from an actual drone in flight.

- **Next:** Carry out in-flight measurement of the small drone.
- **Scientific Question:** Can focused ISAR images be generated from these small drones in flight?

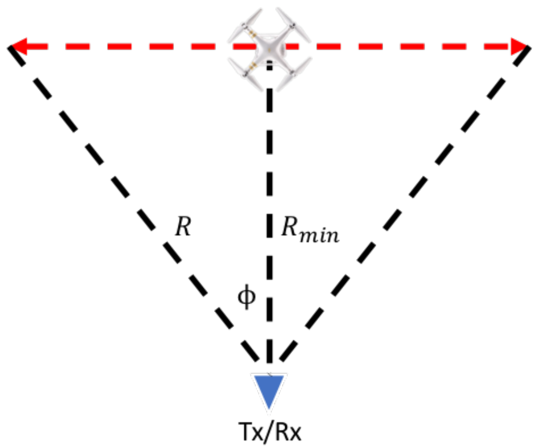
In-Situ Measurement Using a UWB Radar

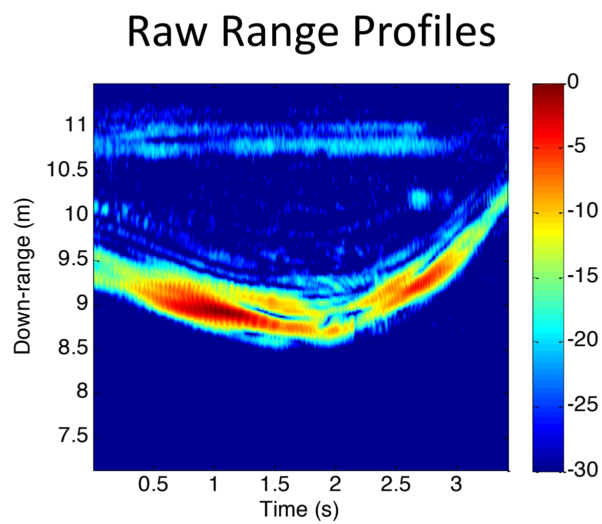
- PulsON 440 (P440) ultra-wideband (UWB) radar by Time Domain Corporation.
- Emits short pulses at a pulse repetition frequency of 10 MHz.
- Equivalent frequency bandwidth from 3.1 to 5.3 GHz centered at 4.3 GHz.

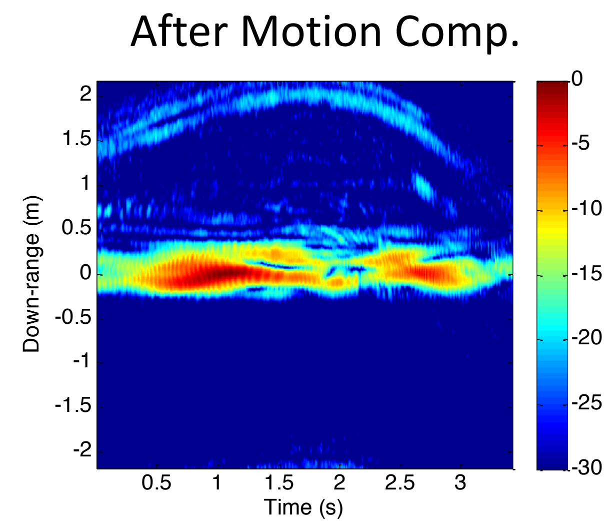
In-Flight Measurement Setup

- Measurement setup on the ground includes P440 radar, circulator, and single horn antenna.
- Phantom 3 Adv. is used since it has extractable GPS flight data.
- Collect range profiles (at 100 Hz) as the drone flies by in a straight line.

Motion Compensation



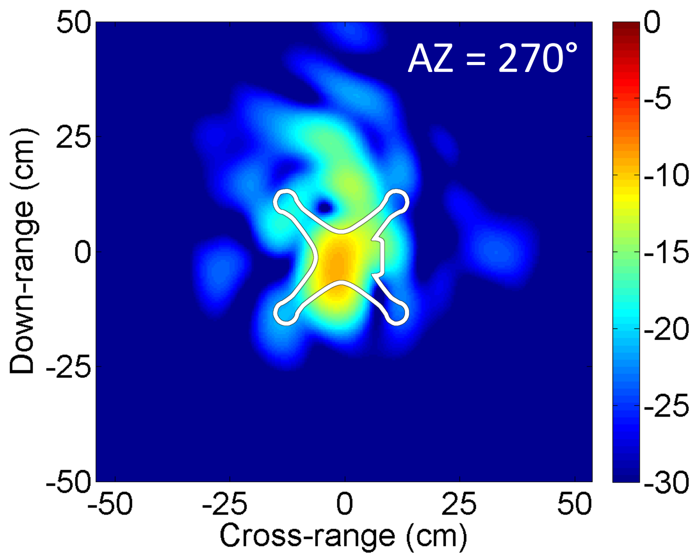




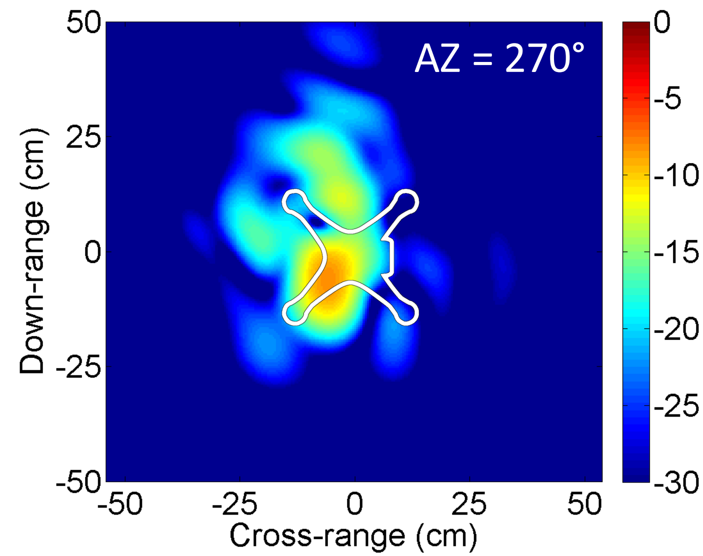
- Motion compensation is necessary to remove translational motion and retain only the rotational motion.
- Images generated through blind motion compensation (alignment of the RCS centroid).
- Baseline images also generated with aid from "ground truth," GPS flight data.
- Angle estimate based on $\phi = \cos^{-1}(R/R_{min})$. Images formed using same *k*-space imaging as before.

Phantom 3 Adv. Results

Blind Motion Compensation

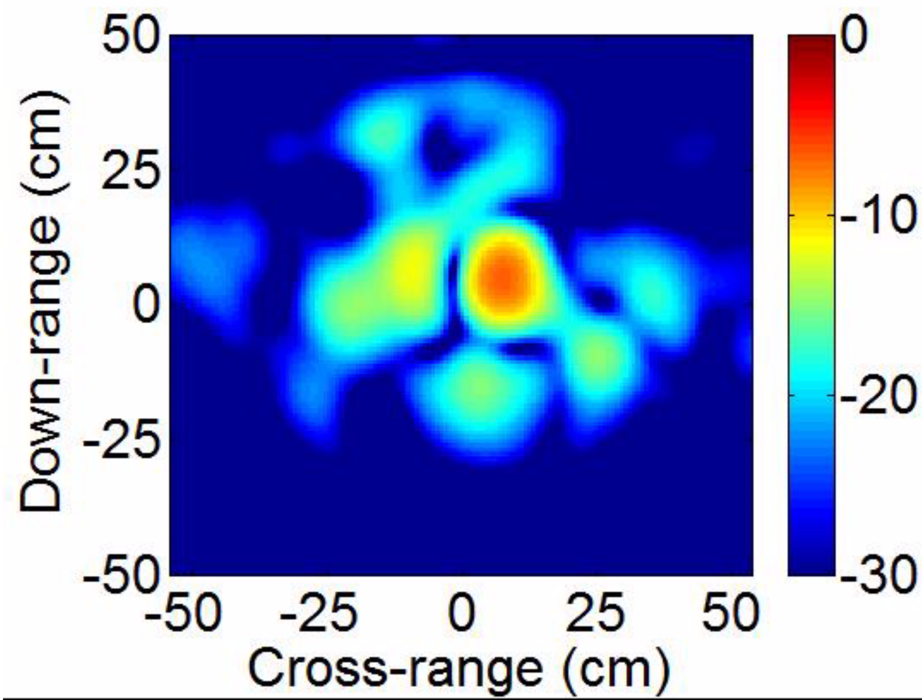


GPS-Assisted Motion Compensation



- Images obtained from blind motion compensation are on-par with images obtained from GPS-assisted motion compensation.
- Images are focused but narrower bandwidth of radar and limited number of scatterers on the drone make it challenging to discern the shape.

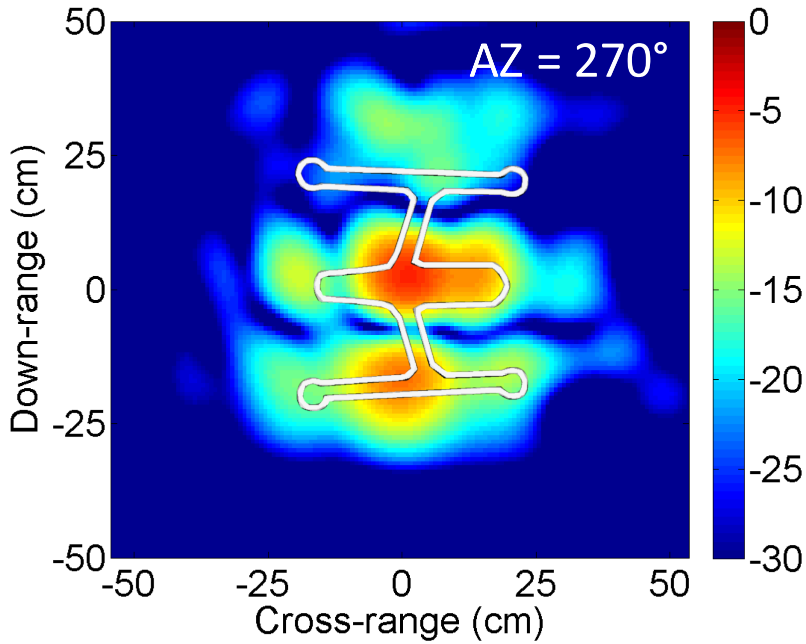
Larger Drone: DJI Inspire 1



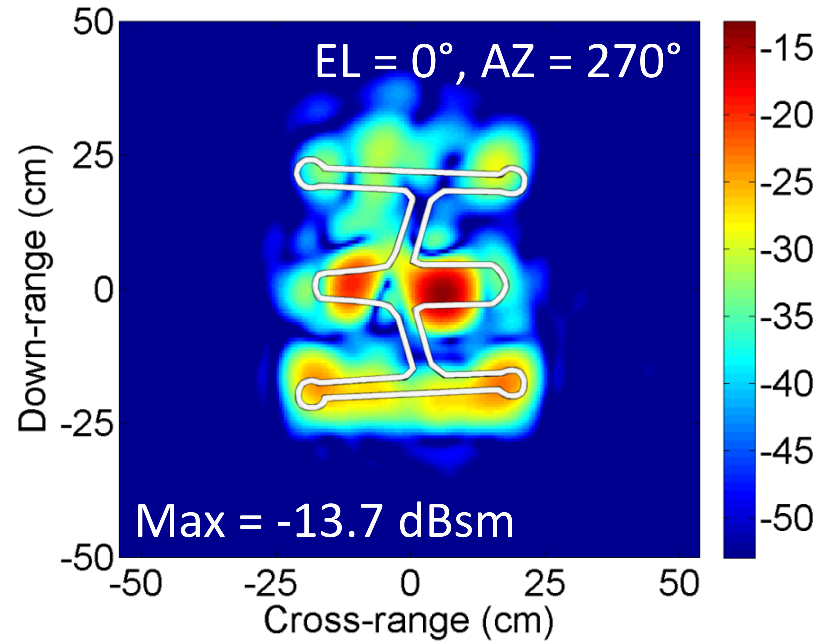
ISAR movie available at: http://users.ece.utexas.edu/~ling/DroneISARMovie_Inspire.gif

Compared to Laboratory Measurement

In-Situ Meas. (3.1-5.3 GHz)



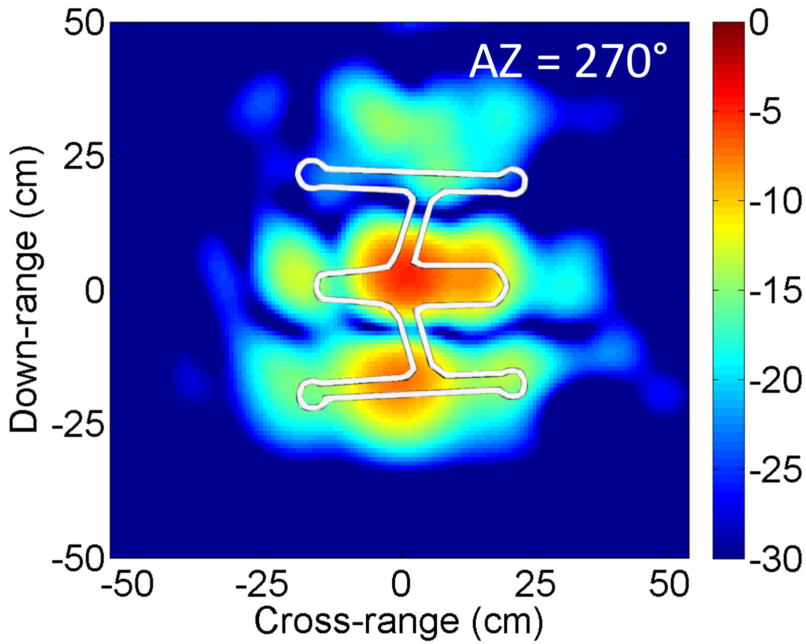
Lab Meas. (3-6 GHz)



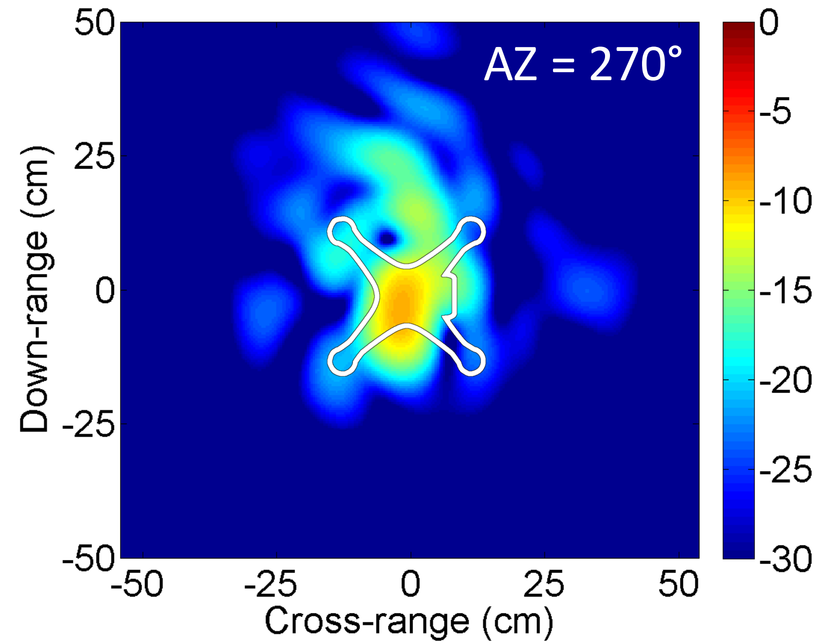
Images after blind motion compensation are comparable to those obtained in laboratory measurement.

Compared to Phantom 3

In-situ Meas. Inspire 1



In-situ Meas. Phantom 3



Size difference, from Phantom 3, is observed.

Conclusion

- ISAR images can capture the drone shape and size despite its small size and low reflectivity.
- Spinning propellers do not contribute significant Doppler clutter.
- Focused images can be generated from in-flight measurement.
- Radar is a potential candidate for tracking and classification of small consumer drones.

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Colton Bostick of UAV Direct and Lenny Tropiano of FlyTheSkyDrone Productions for providing drones for measurement.

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