

RCS Calculation and Receiver Position Optimization

for Drone and Drone Swarm Detection

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Abstract

Using the Finite Difference Time Domain (FDTD) method, the bistatic Radar Cross Section (RCS) of a single drone was calculated using the results of a total-field/scattered-field (TFSF) simulation with a 1GHz Blackman-Harris windowed sine wave. An array factor was developed for the scattered field from an incident plane wave. The RCS from a group of drones was calculated using this array factor. The total RCS was found from two groups of simultaneous waves. The first group of simultaneous excitation waves had incident phi directions from 0 to 315° in steps of 45° (inclusive) with an incident theta of 45°. The second group had incident phi angles as before with incident theta of 135°. The ideal receiver position for detection from these simultaneous excitation groups was determined.

Introduction

As drones become more common in consumer and military applications, it is important to understand their radar appearance. The RCS is a measure of the amount of power reflected by an object [1]. Understanding an object's RCS assists with identifying it on radar. Bistatic RCS is the RCS with different incident and reception angles. This is harder to defeat with stealth design. The FDTD method is a direct solution method of numerically solving Maxwell's differential equations on spatial grids in the time domain [2]. This author was unable to find analysis of a consumer drone or drone swarm's bistatic RCS. Using the FDTD method, this project will find the bistatic RCS of a consumer drone and group of drones.

Simulation Setup

- Consumer first person view drone model from [3] with approximate dimensions 0.5m x 0.5m x 0.12m.
- Material properties set based on available information and restricted to linear and isotropic.
- A Blackman-Harris windowed sine wave with a frequency of 1GHz, amplitude of 1V, and window from 0 to 5T was used.
- TFSF technique was used with the FDTD method to obtain the scattered field from drone.
- Bistatic RCS calculated by processing scattered field data.

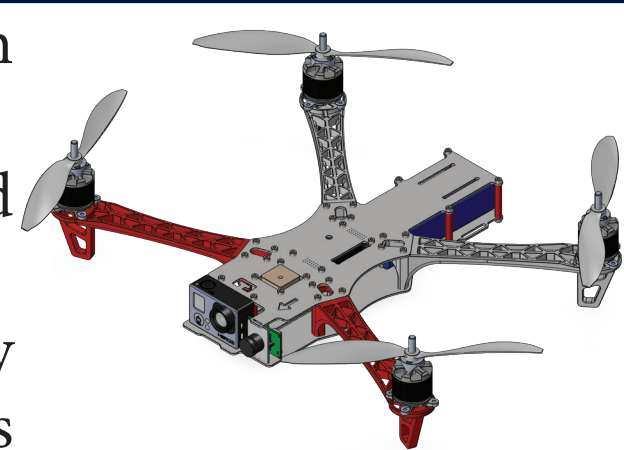
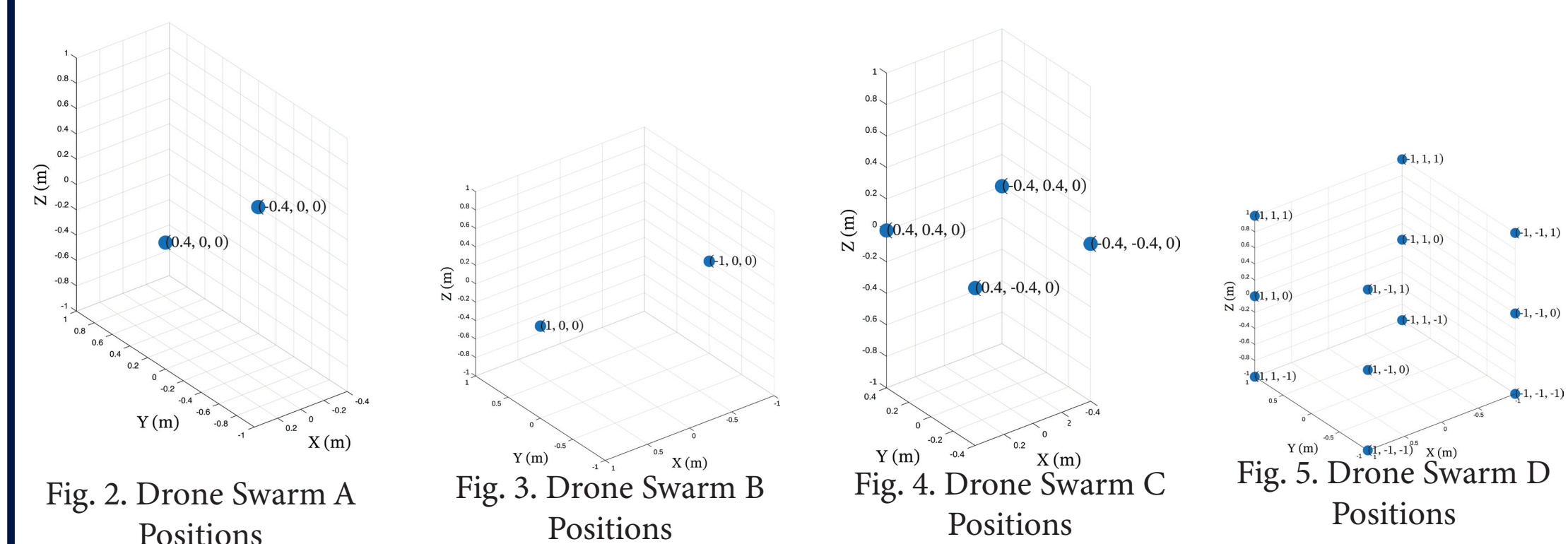


Fig. 1. Drone CAD Model

Array Factor

- The array factor is a function of the array geometry and the excitation phase [4].
- The excitation phase shift is the difference in phase the incident wave travels in the $\hat{k}$ direction from the reference object to the specific object's position.
- The array factor from a scattered response is the following, where N is the number of objects, $\vec{r}_i$ is the position of element i, $\hat{k}$ is the incident wavevector, and $\vec{r}$ is an observation vector ($R_{\text{ref}}, \theta, \phi$):
$$\tilde{F}(\theta, \phi) = \sum_{i=1}^N \exp(jk(\vec{r}_i \cdot \hat{r} - \vec{r}_i \cdot \hat{k}))$$
- The array factor is calculated for the following drone swarms:



Radar Cross Section

- Radar Cross Section (RCS) is a measure of the amount of power reflected by an object [1].
- Three-dimensional bistatic RCS is defined as [2]:
$$\text{RCS}(\theta, \phi) = \lim_{r \rightarrow \infty} (4\pi r^2 P_{\text{scat}} / P_{\text{inc}})$$
- Because $P \propto E^2$ and the array factor is derived such that $\tilde{E}_{\text{tot}} = \tilde{E}_{\text{single}} \tilde{F}$ [4], the array RCS is:
$$\text{RCS}_{\text{arr}}(\theta, \phi) = \text{RCS}(\theta, \phi) |\tilde{F}(\theta, \phi)|^2$$
- The following are various RCS for single drones and drone swarms. All color axes reference Fig. 6.

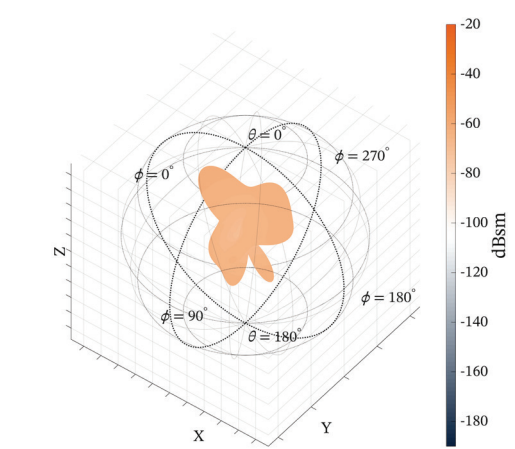


Fig. 6. Drone RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=45^\circ$

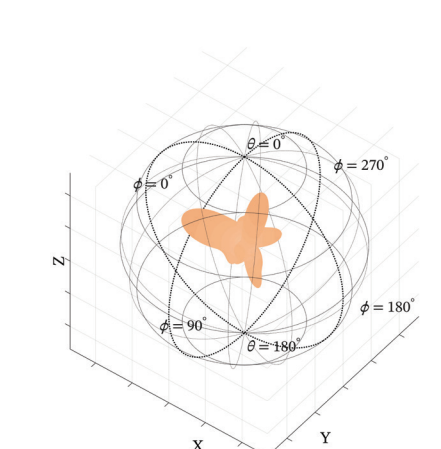


Fig. 7. Drone RCS $\phi_{\text{inc}}=45^\circ$ and $\theta_{\text{inc}}=45^\circ$

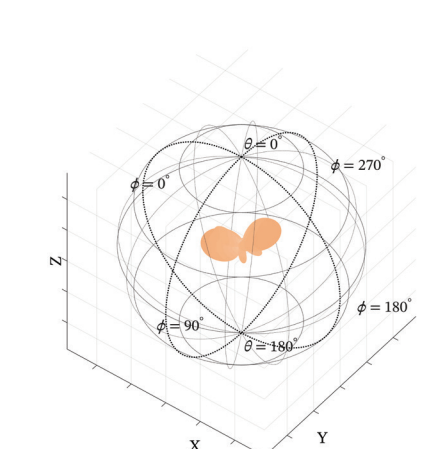


Fig. 8. Drone RCS $\phi_{\text{inc}}=90^\circ$ and $\theta_{\text{inc}}=45^\circ$

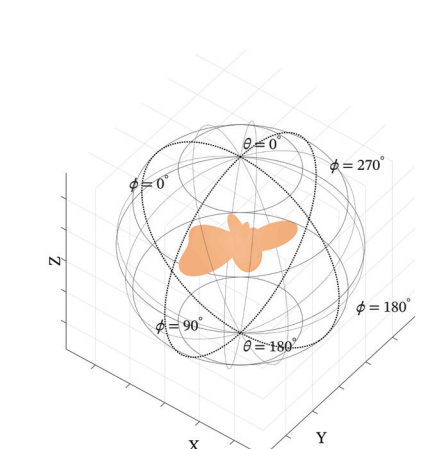


Fig. 9. Drone RCS $\phi_{\text{inc}}=135^\circ$ and $\theta_{\text{inc}}=45^\circ$

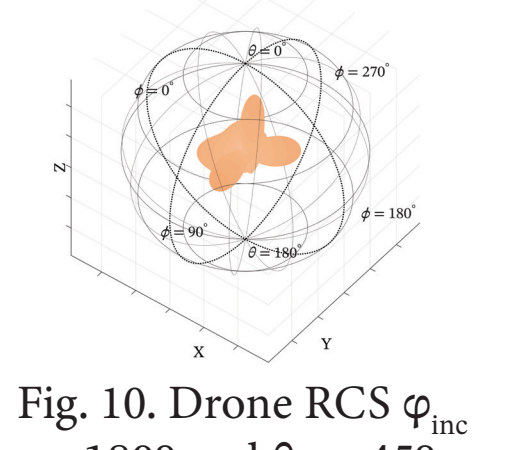


Fig. 10. Drone RCS $\phi_{\text{inc}}=180^\circ$ and $\theta_{\text{inc}}=45^\circ$

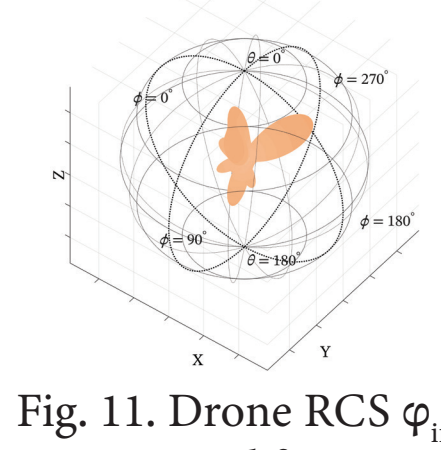


Fig. 11. Drone RCS $\phi_{\text{inc}}=225^\circ$ and $\theta_{\text{inc}}=45^\circ$

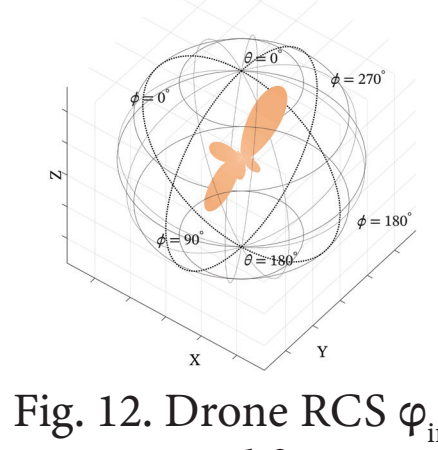


Fig. 12. Drone RCS $\phi_{\text{inc}}=270^\circ$ and $\theta_{\text{inc}}=45^\circ$

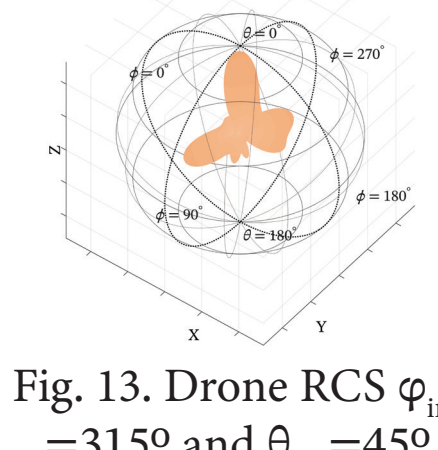


Fig. 13. Drone RCS $\phi_{\text{inc}}=315^\circ$ and $\theta_{\text{inc}}=45^\circ$

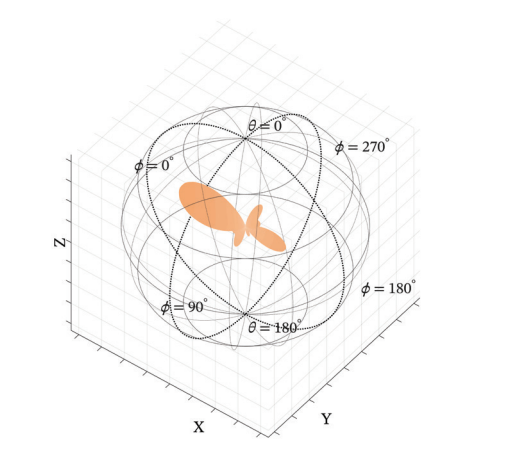


Fig. 14. Drone RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=90^\circ$

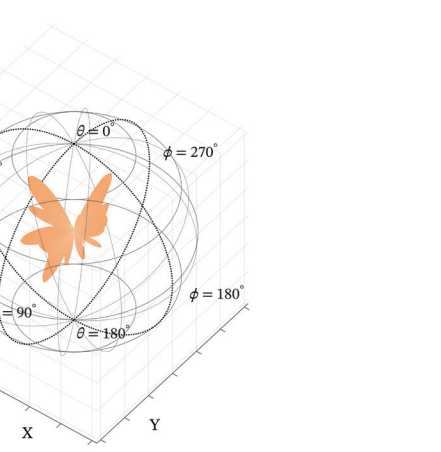


Fig. 15. Drone Swarm A RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=90^\circ$

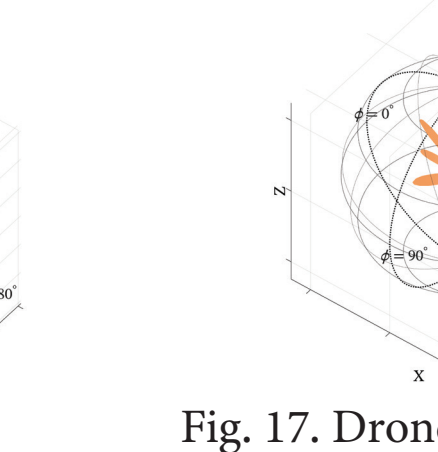


Fig. 16. Drone Swarm B RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=90^\circ$

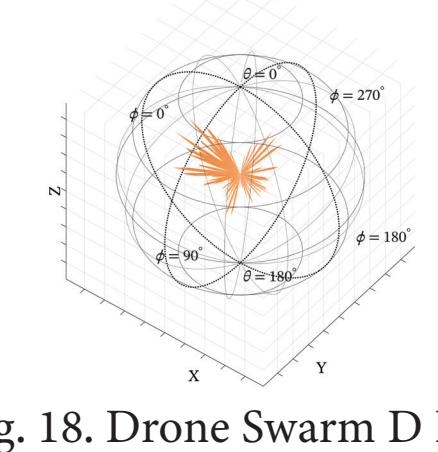


Fig. 17. Drone Swarm C RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=90^\circ$

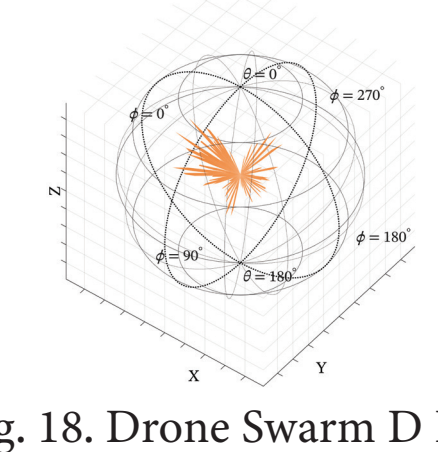


Fig. 18. Drone Swarm D RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=90^\circ$

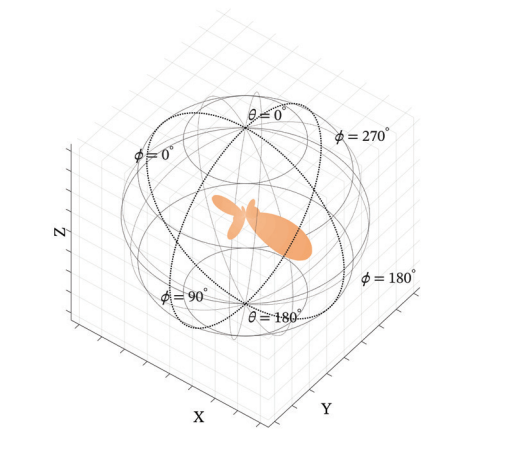


Fig. 19. Drone RCS $\phi_{\text{inc}}=180^\circ$ and $\theta_{\text{inc}}=90^\circ$

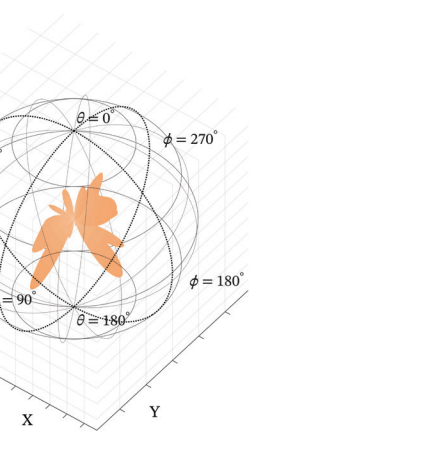


Fig. 20. Drone Swarm A RCS $\phi_{\text{inc}}=180^\circ$ and $\theta_{\text{inc}}=90^\circ$

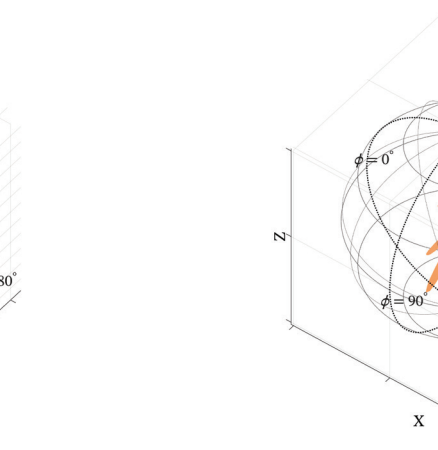


Fig. 21. Drone Swarm B RCS $\phi_{\text{inc}}=180^\circ$ and $\theta_{\text{inc}}=90^\circ$

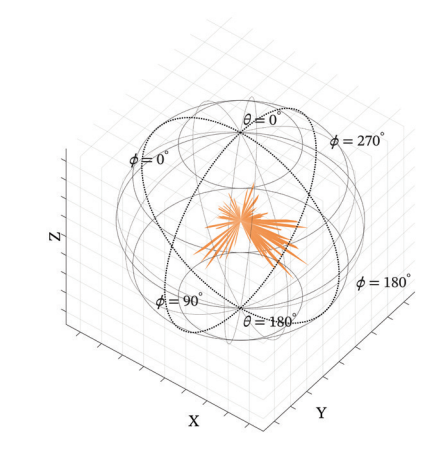


Fig. 22. Drone Swarm C RCS $\phi_{\text{inc}}=180^\circ$ and $\theta_{\text{inc}}=90^\circ$

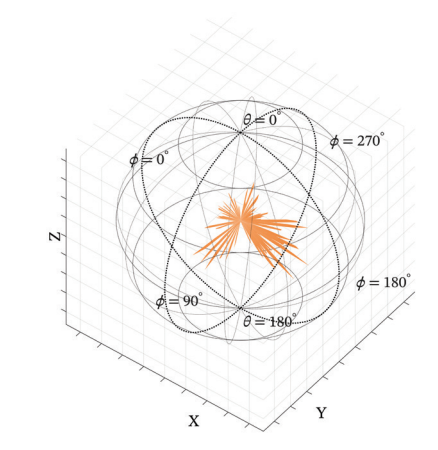


Fig. 23. Drone Swarm D RCS $\phi_{\text{inc}}=180^\circ$ and $\theta_{\text{inc}}=90^\circ$

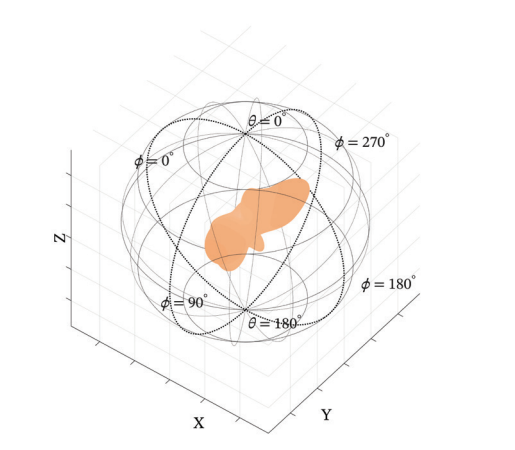


Fig. 24. Drone RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=135^\circ$

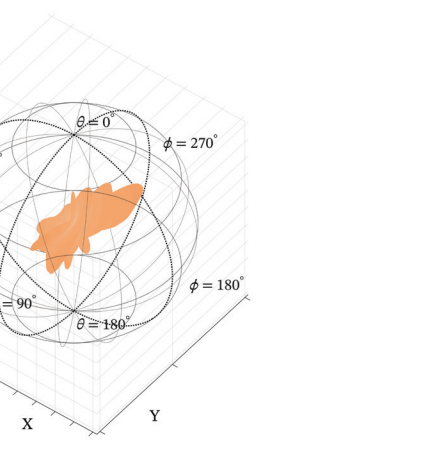


Fig. 25. Drone Swarm A RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=135^\circ$

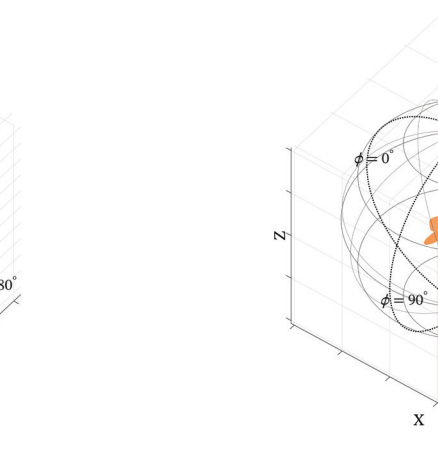


Fig. 26. Drone Swarm B RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=135^\circ$

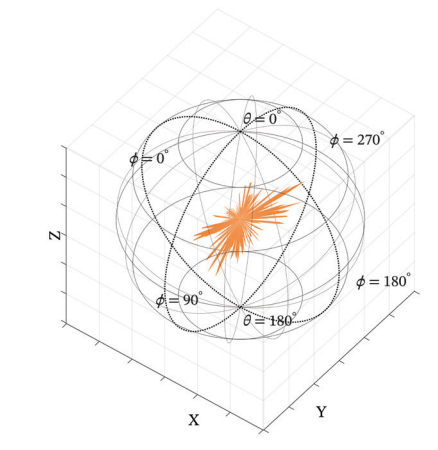


Fig. 27. Drone Swarm C RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=135^\circ$

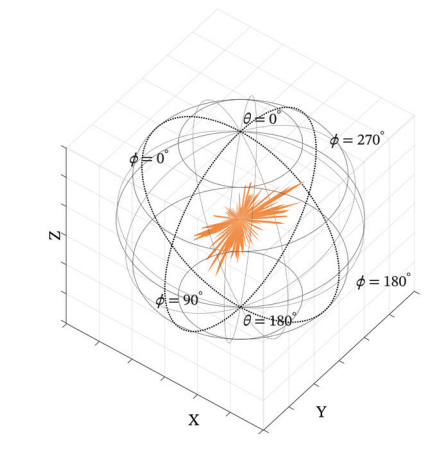


Fig. 28. Drone Swarm D RCS $\phi_{\text{inc}}=0^\circ$ and $\theta_{\text{inc}}=135^\circ$

Simultaneous Excitation

- Two groups of simulations were run with ϕ_{inc} from 0 to 315° in steps of 45° degrees and θ_{inc} at 45° (Fig. 29) and ϕ_{inc} as before with θ_{inc} at 135° (Fig. 30).
- The resulting scattered electric fields were summed to calculate P_{scat} and the total RCS from each group of waves.

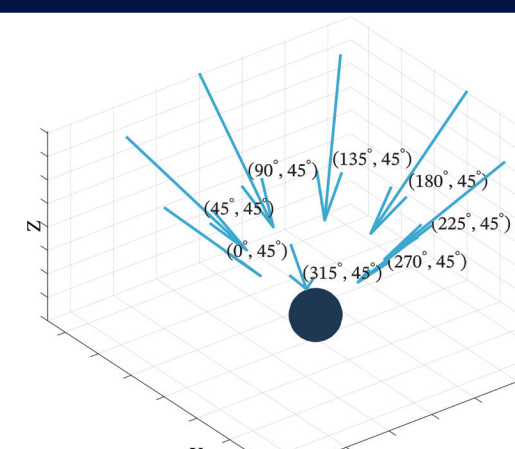


Fig. 29. Simultaneous Excitation Directions with $\theta_{\text{inc}}=45^\circ$

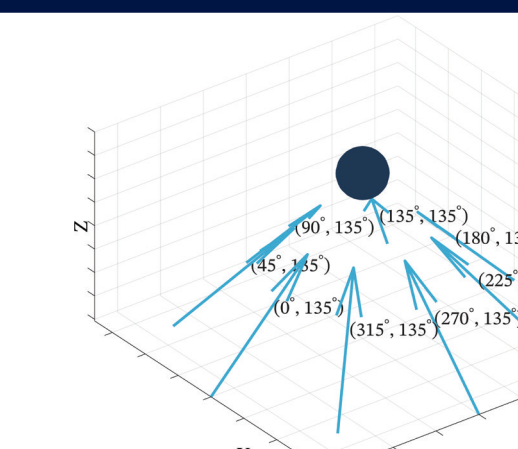


Fig. 30. Simultaneous Excitation Directions with $\theta_{\text{inc}}=135^\circ$

Ideal Receiver Position

- The ideal ground receiver position direction for detection was found as the direction of greatest RCS magnitude in the lower hemisphere ($\theta > 90^\circ$).
- The following are the simultaneous excitation RCS with the maximum reflection direction (all color axes reference Fig. 31):

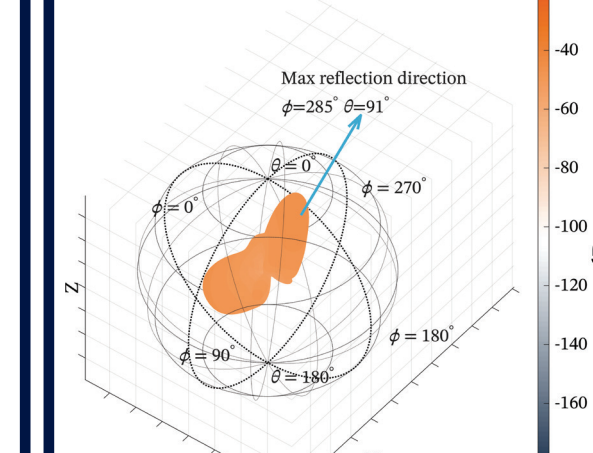


Fig. 31. Combined RCS of Drone with $\theta_{\text{inc}}=45^\circ$

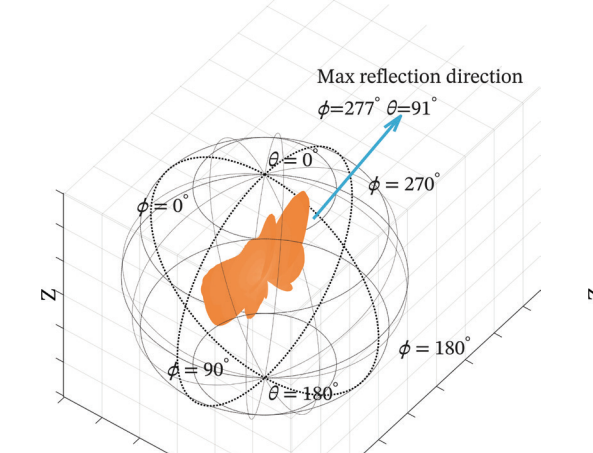


Fig. 32. Combined RCS of Drone Swarm A with $\theta_{\text{inc}}=45^\circ$

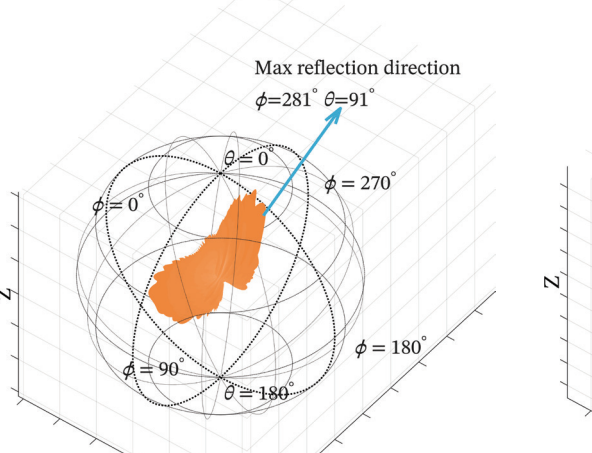


Fig. 33. Combined RCS of Drone Swarm B with $\theta_{\text{inc}}=45^\circ$

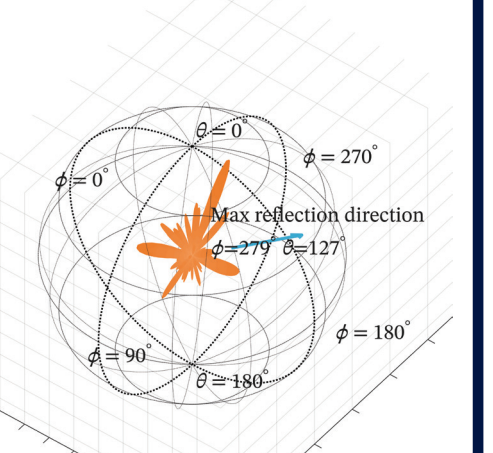


Fig. 34. Combined RCS of Drone Swarm C with $\theta_{\text{inc}}=45^\circ$

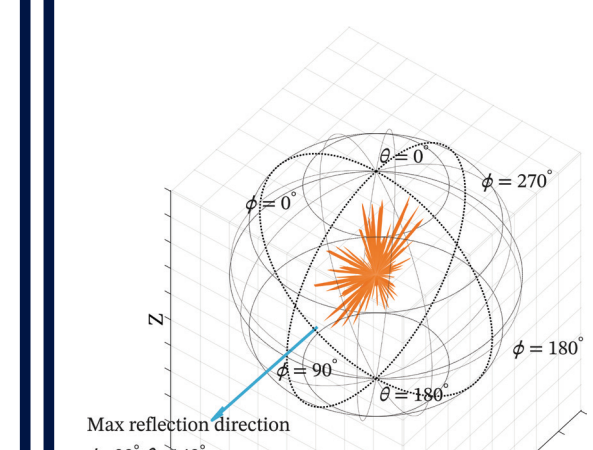


Fig. 35. Combined RCS of Drone Swarm D with $\theta_{\text{inc}}=45^\circ$

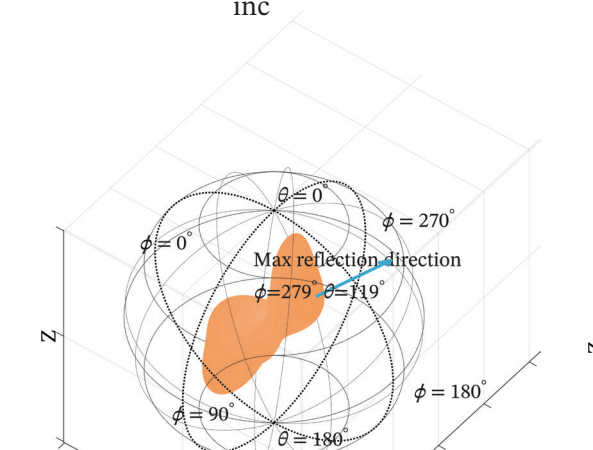


Fig. 36. Combined RCS of Drone with $\theta_{\text{inc}}=135^\circ$

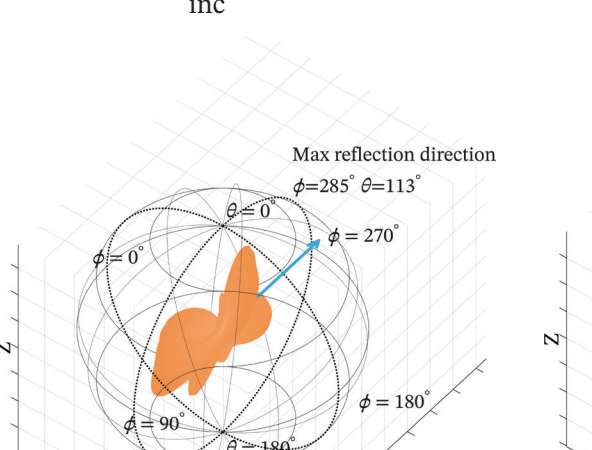


Fig. 37. Combined RCS of Drone Swarm A with $\theta_{\text{inc}}=135^\circ$

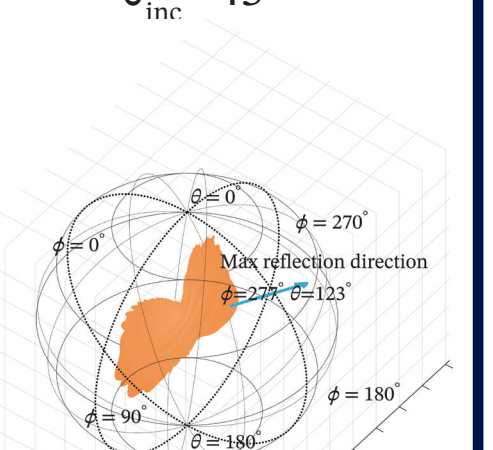


Fig. 38. Combined RCS of Drone Swarm B with $\theta_{\text{inc}}=135^\circ$

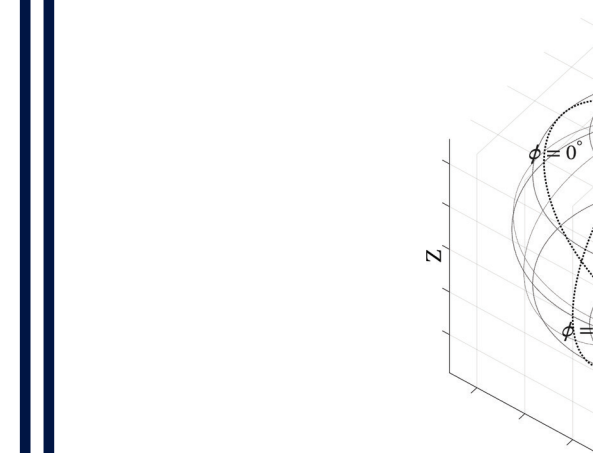


Fig. 39. Combined RCS of Drone Swarm C with $\theta_{\text{inc}}=135^\circ$

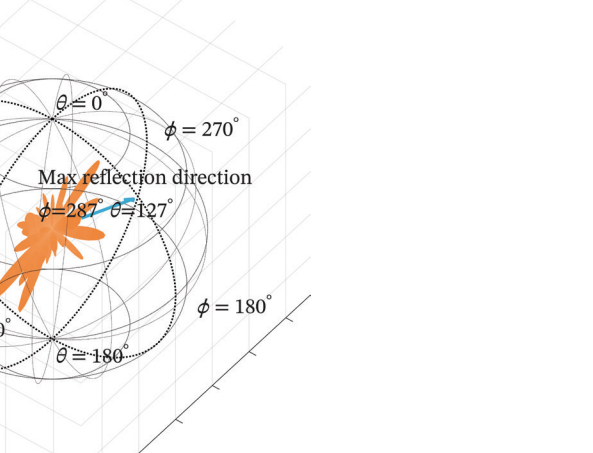


Fig. 40. Combined RCS of Drone Swarm D with $\theta_{\text{inc}}=135^\circ$

Summary and Discussion

The bistatic radar cross sections of a single drone at 1GHz was found. It has a maximum magnitude of about -60dBsm. An array factor for a scattering array was developed and used to find the RCS of a swarm of drones. For the configurations calculated, the maximum magnitude generally increased as the number of drones increased. The RCS was found for a drone and group of drones being simultaneously excited by several incident waves. The direction with the maximum RCS from the simultaneous excitation was determined. At higher spacing and number of drones, grating lobes could be seen on the RCS. The direction of maximum reflection was similar to a single drone for small swarms, but varied as number and spacing increased.

Future Work

The bistatic RCS for a drone and group of drones were found. Implementing an analytical field propagator would decrease error in this RCS. Mutual coupling was ignored. Accounting for mutual coupling would provide more realistic results. Different frequencies could be used to identify under which frequencies the drone and drone swarm are most visible and reduce grating lobes seen with higher spacing at 1GHz.

References

- [1] S. M. Wentworth, *Applied Electromagnetics: Early Transmission Lines Approach*, 2nd ed. Hoboken, NJ, USA: Wiley, 2025.
- [2] A. Taflov and S. C. Hagness, *Computational Electrodynamics; The Finite-Difference Time-Domain Method*, 2nd ed. Boston, MA, USA: Artech House, 2000.
- [3] Palacita Concepts. "Team-blacksheep Discovery." Grab Cad. <https://grabcad.com/library/team-blacksheep-discovery-1> (accessed May 27, 2026).
- [4] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: Wiley, 2016.