



Define Minimum Safe Operational Volume for Aerial Vehicles in Upper Class E Airspace

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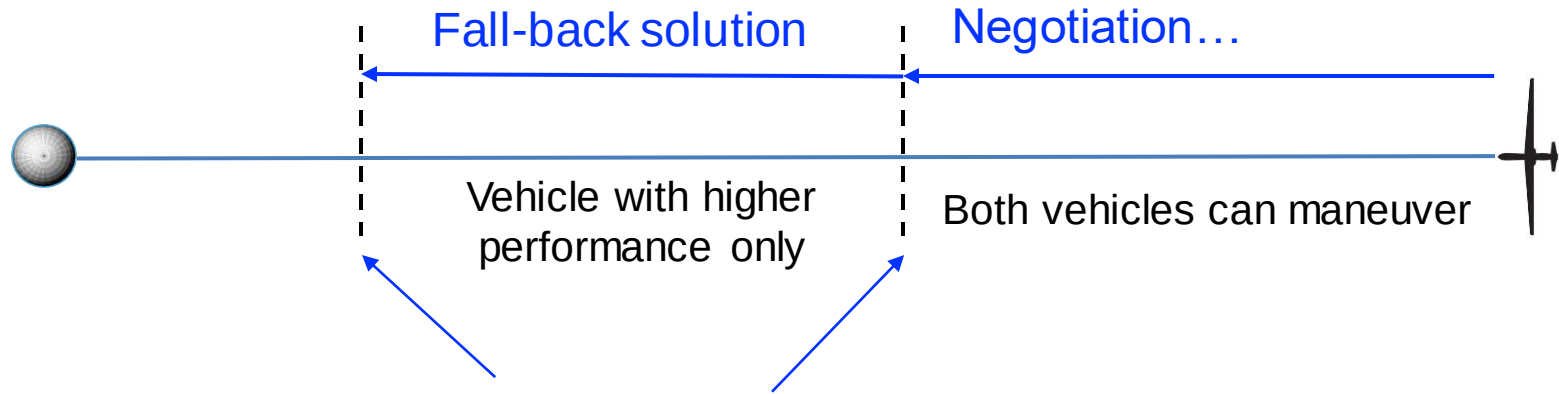
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Motivation



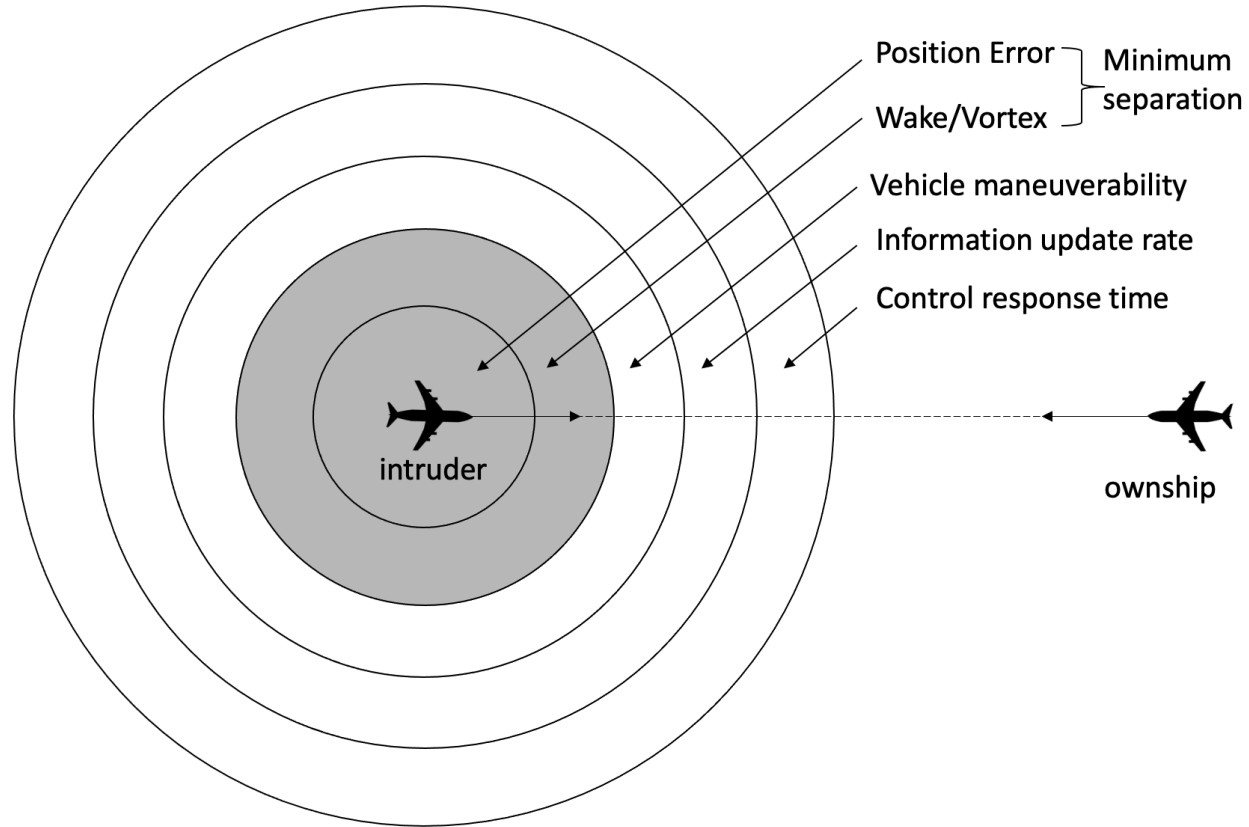
Cooperative operation concept for upper Class E airspace traffic management.



Where is the minimum safe operational boundary?



Contributing Factors



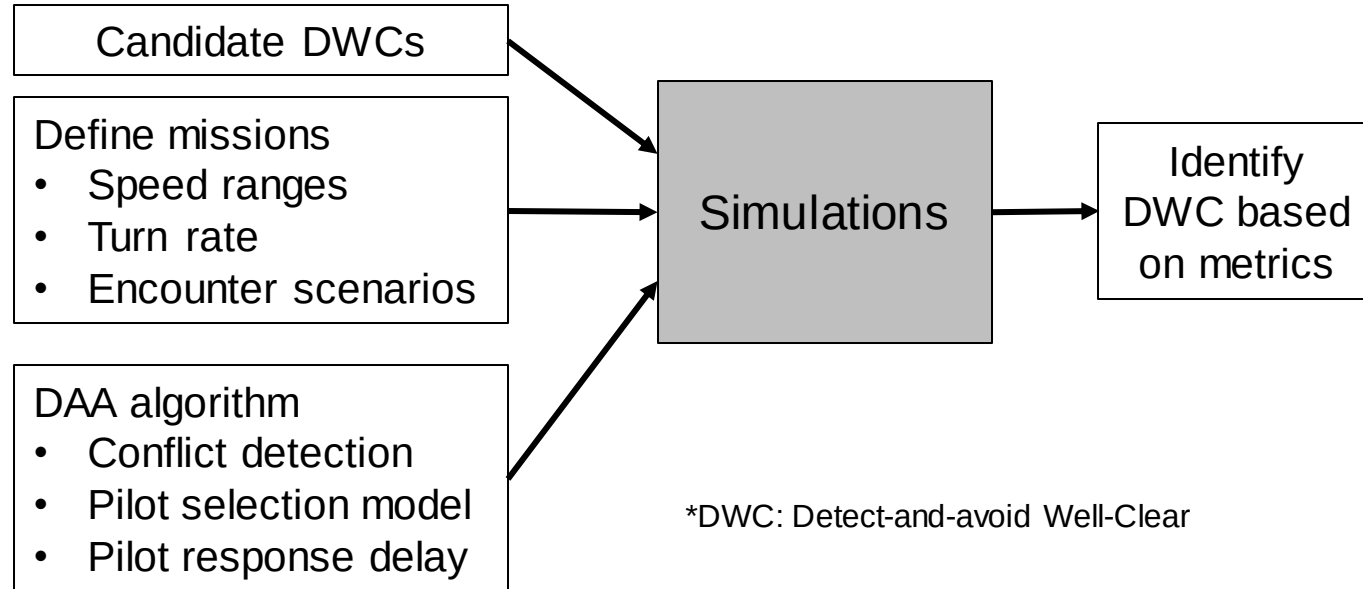
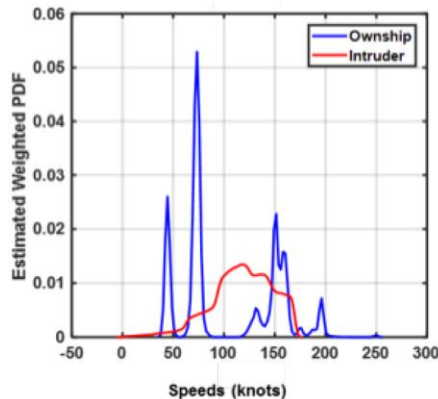


Past approach won't work

Fixed DWC*

Mission dependent

- Speed, altitude
- Turn rate (7°/s)



*DWC: Detect-and-avoid Well-Clear

- One-size-fits-all
- Mission dependent
- Fundamental understanding
- Initial estimation is needed

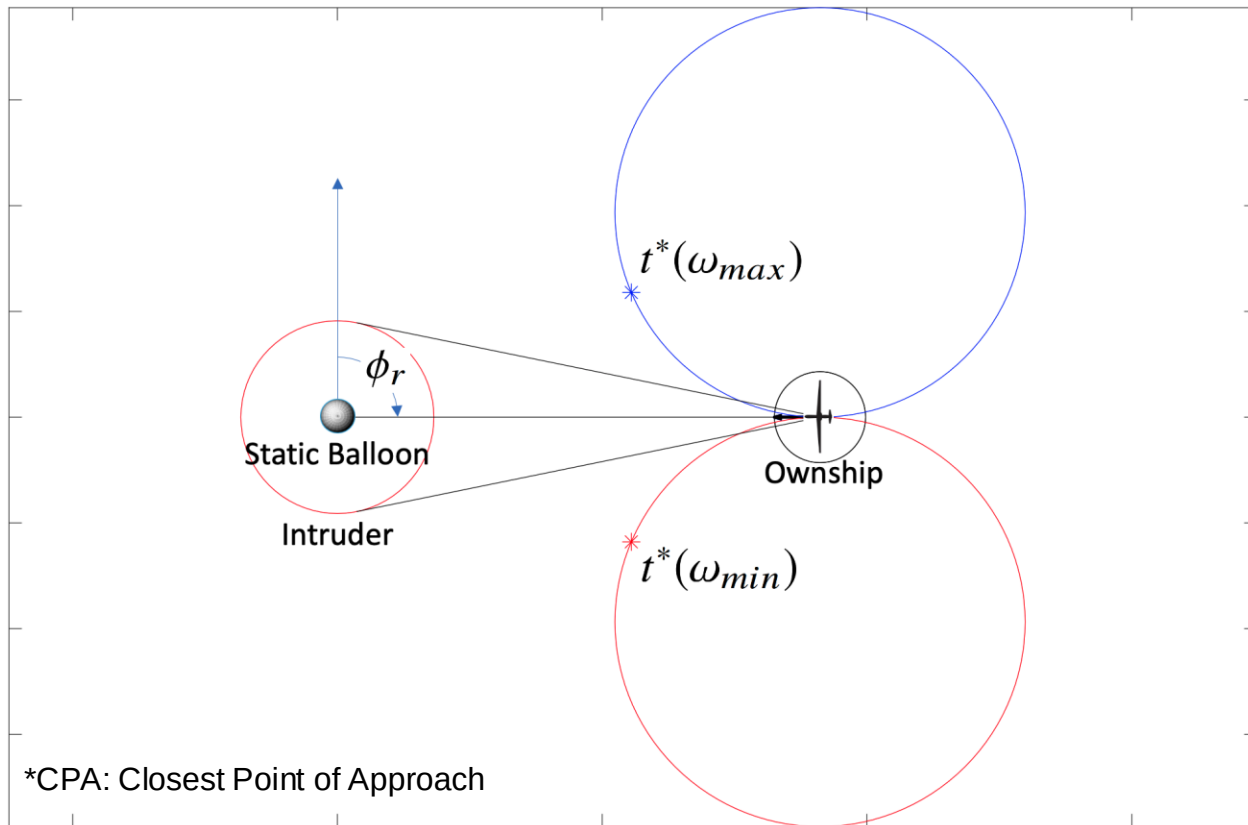
[1] Gilbert Wu, et. al. , “Detect-and-Avoid Closed-Loop Evaluation of Non-Cooperative Well Clear Definitions”, 2019.



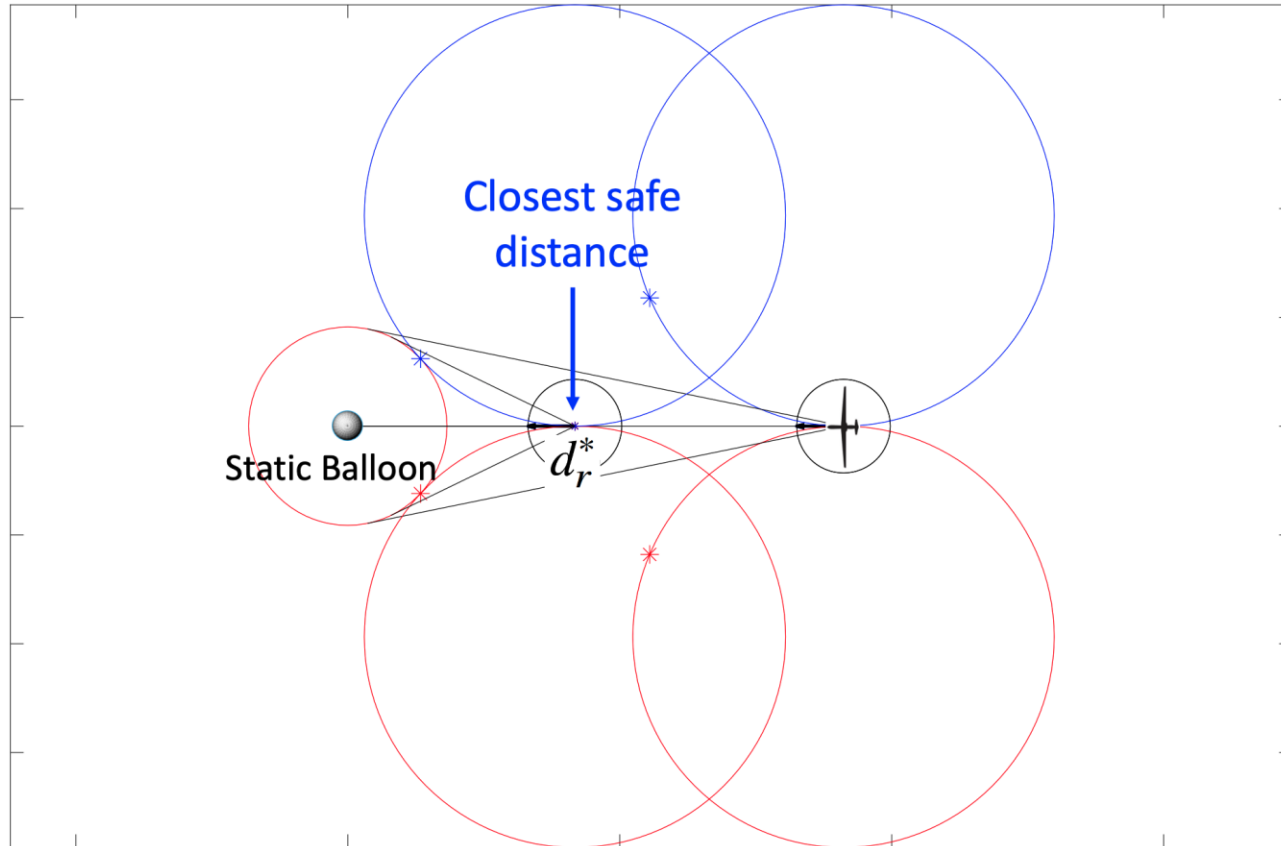
Outline

- Algorithm & demonstration:
 - Global Hawk vs. Balloon
 - Global Hawk vs. Aurora Odyssey
 - Quad-rotor vs. Quad-rotor
- Sensitivity study
 - Velocity
 - Bank angle (not presented here)
 - Minimum Separation (not presented here)
 - Delay caused by communication latency and control response (not presented here)
- Simulation verification
- Conclusions

Step I: Find CPA* with the max. and min. turns

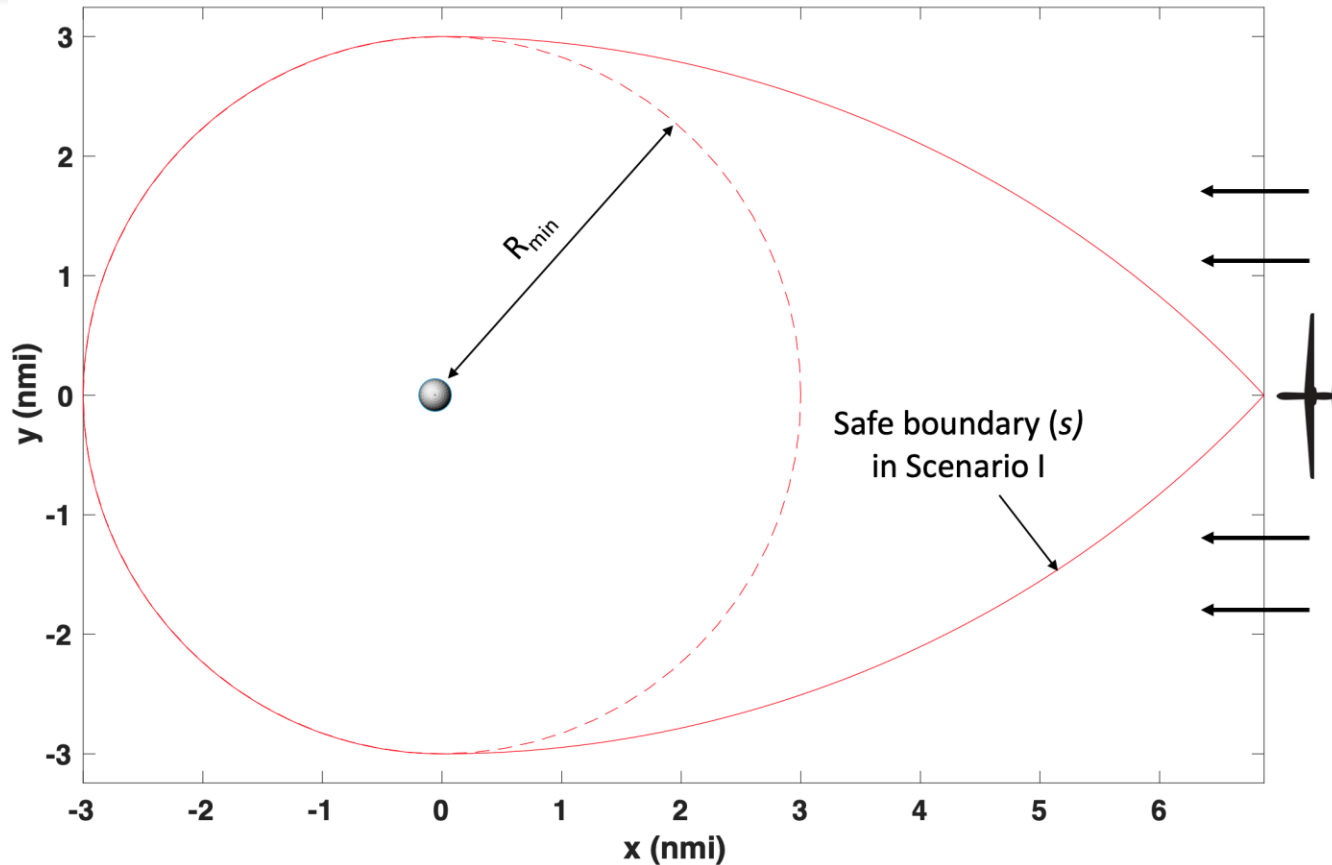


Step II: Find the closest safe distance





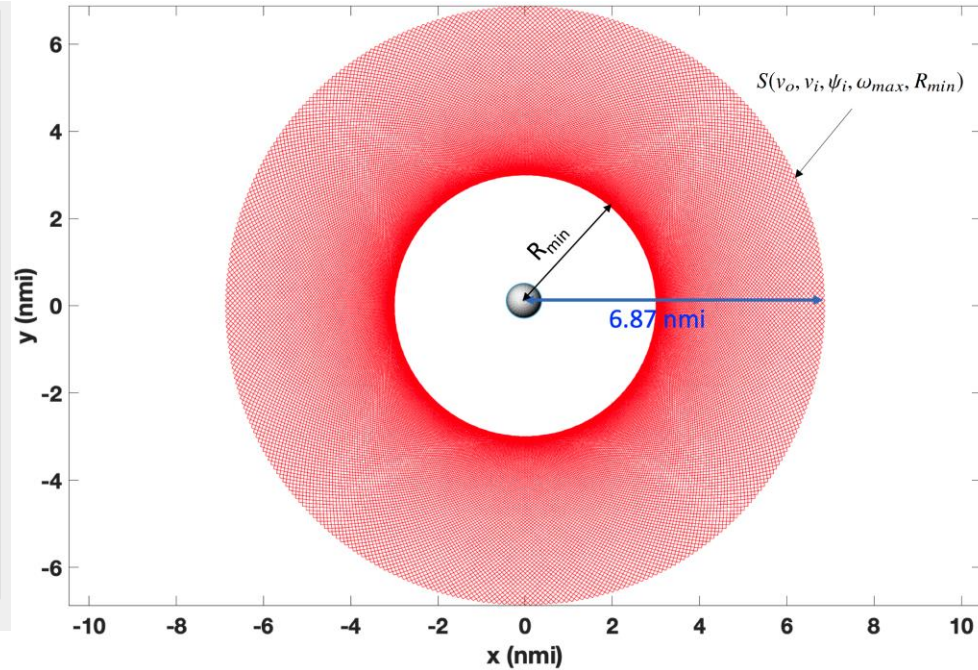
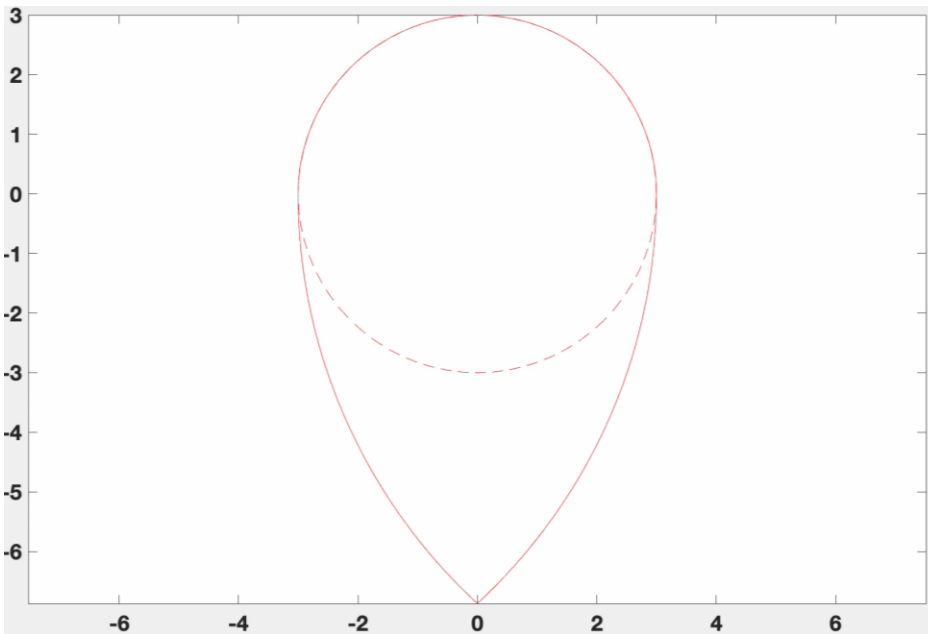
Step III: Safe Operational Boundary for Westbound Aircraft





Step IV: Aggregated minimum safe operational boundary

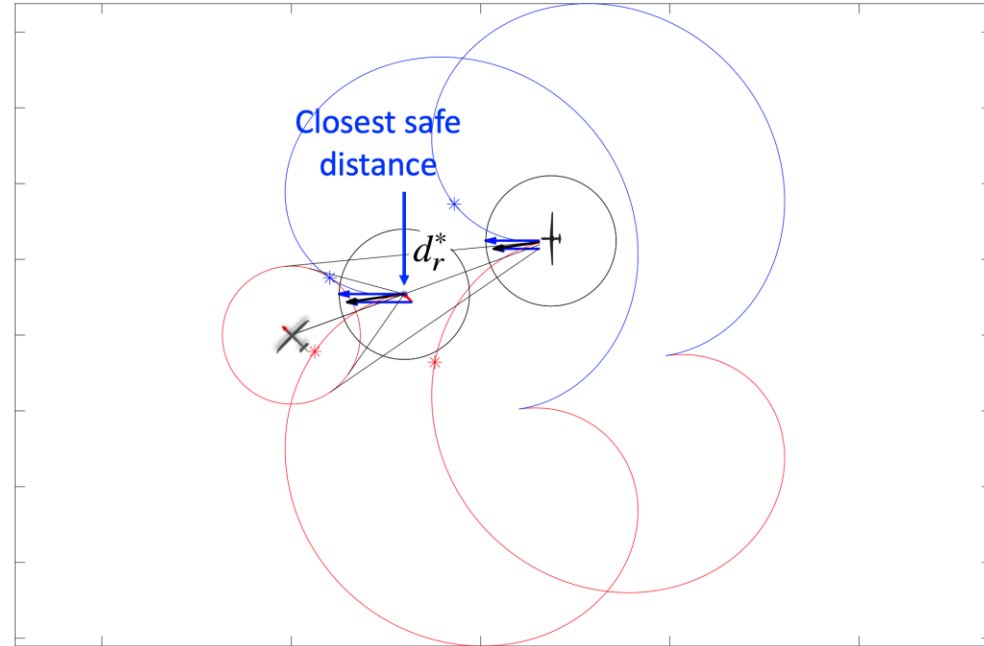
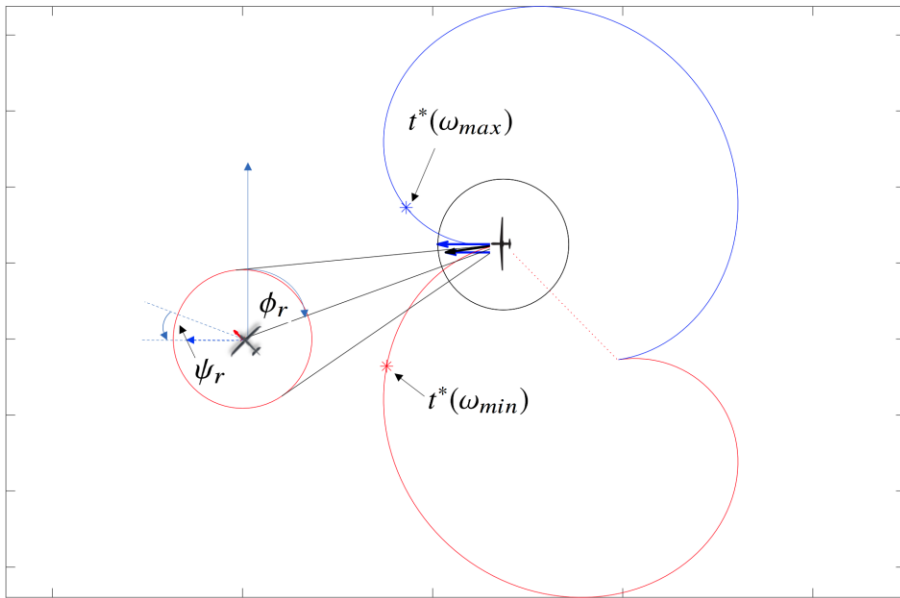
Global Hawk vs. balloon: Global Hawk @340 kts with 14.8° bank; Static balloon





Scenario II: Global Hawk vs. Aurora Odysseus (I & II)

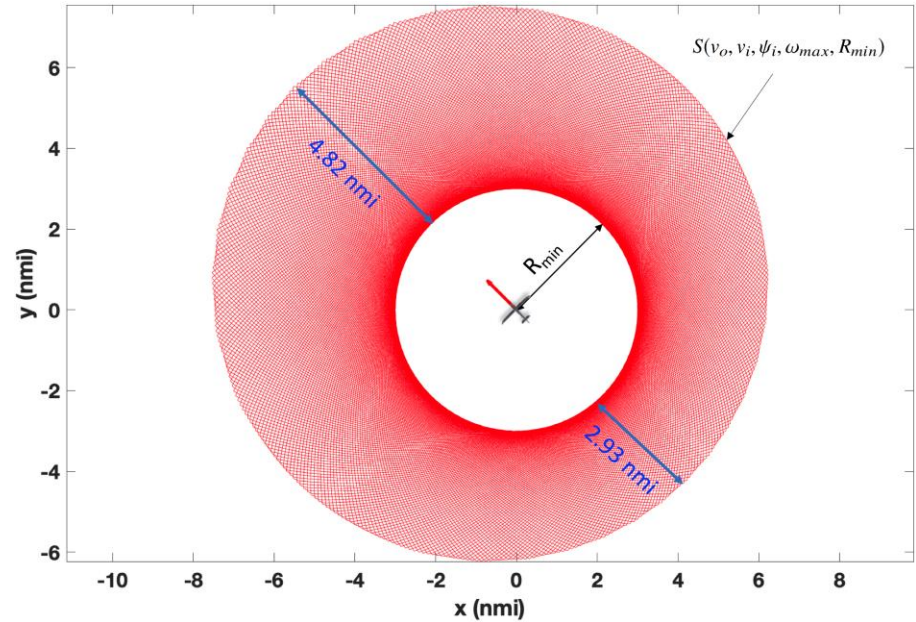
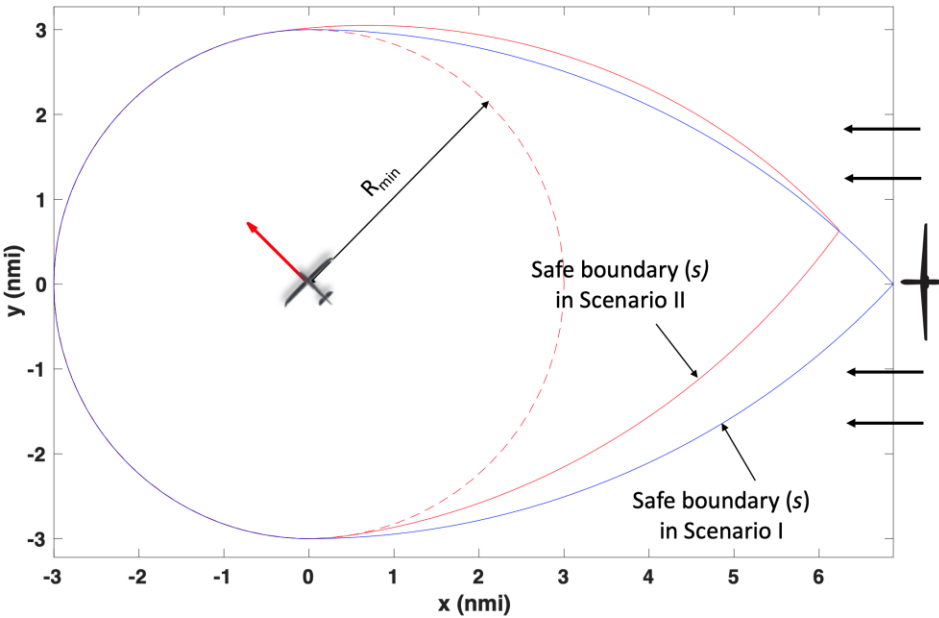
Global Hawk @340 kts with 14.8° bank; Aurora 60 kts





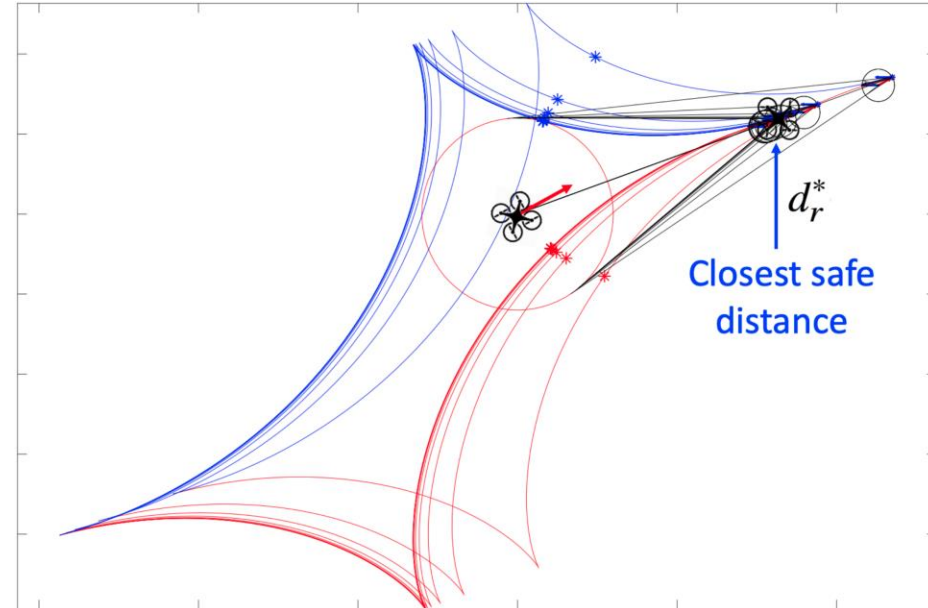
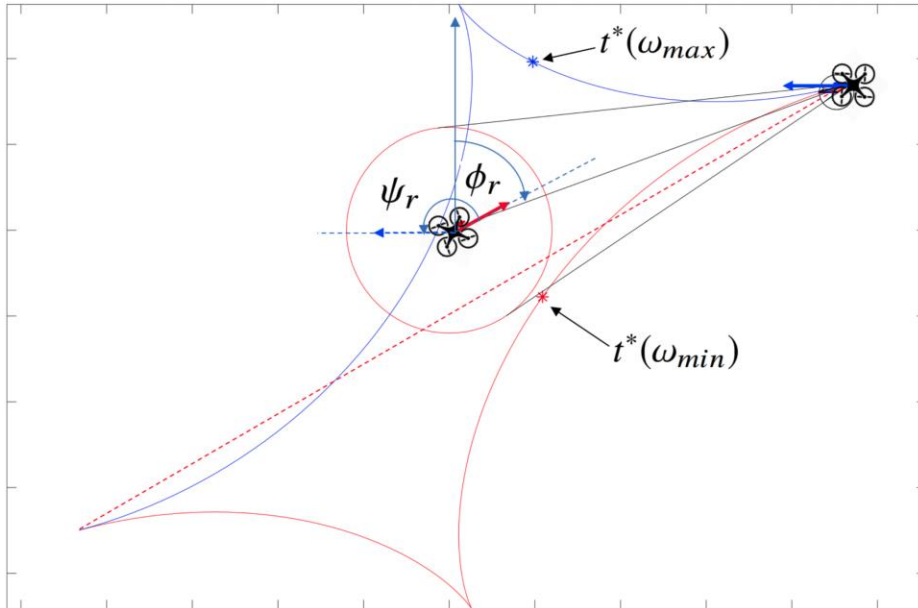
Scenario II: Global Hawk vs. Aurora Odysseus (III & IV)

Global Hawk @340 kts with 14.8° bank; Aurora 60 kts



Scenario III: aircraft with the same speed (I & II)

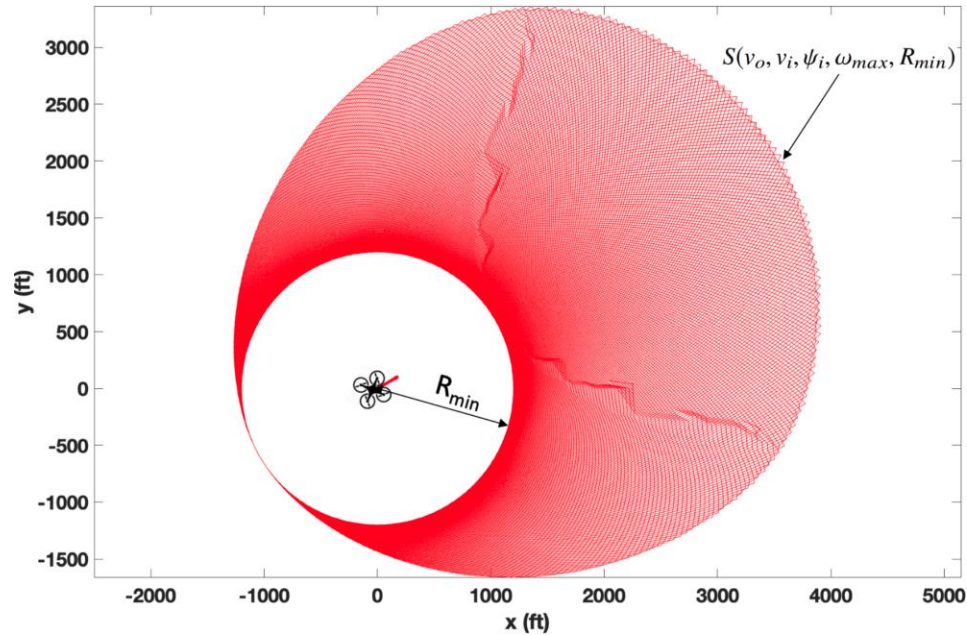
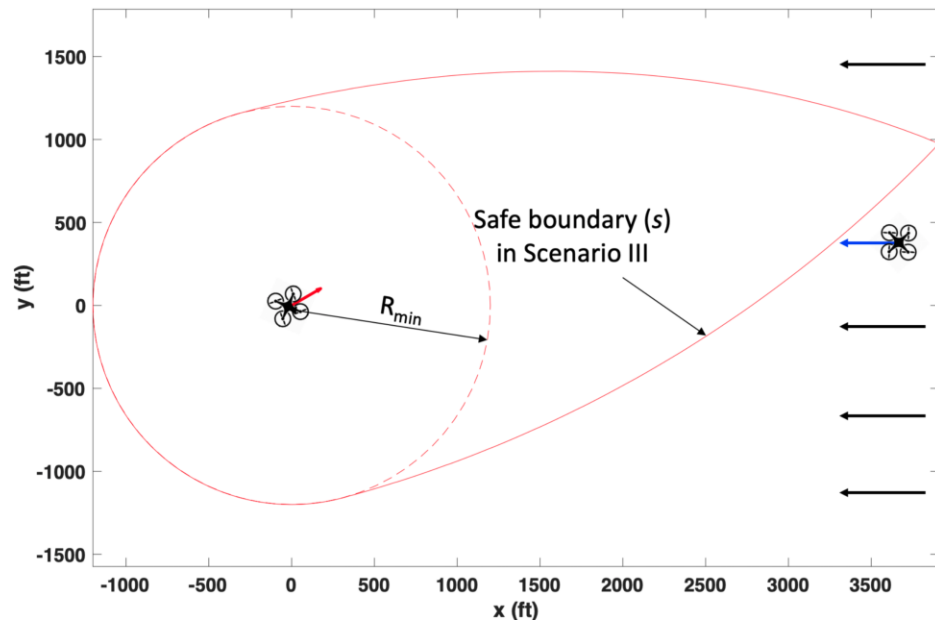
@120 kts with 25° bank





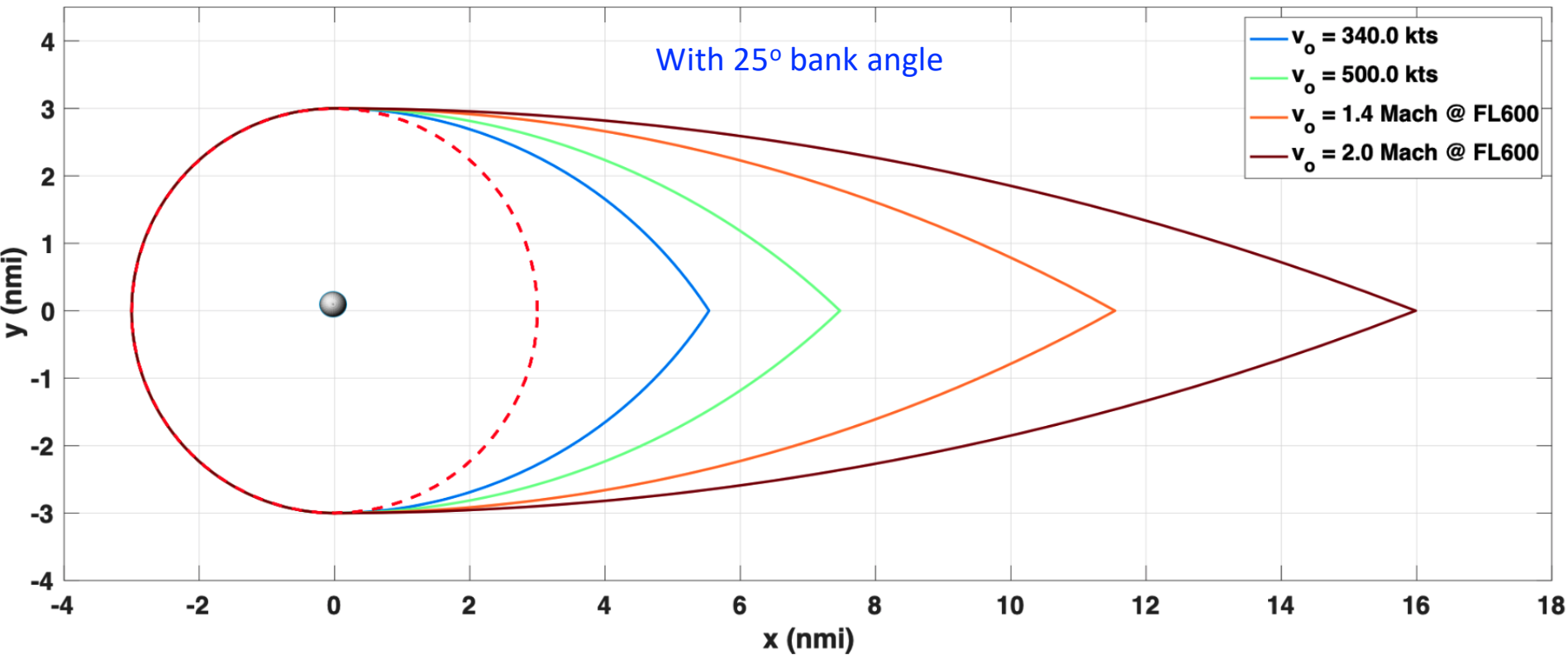
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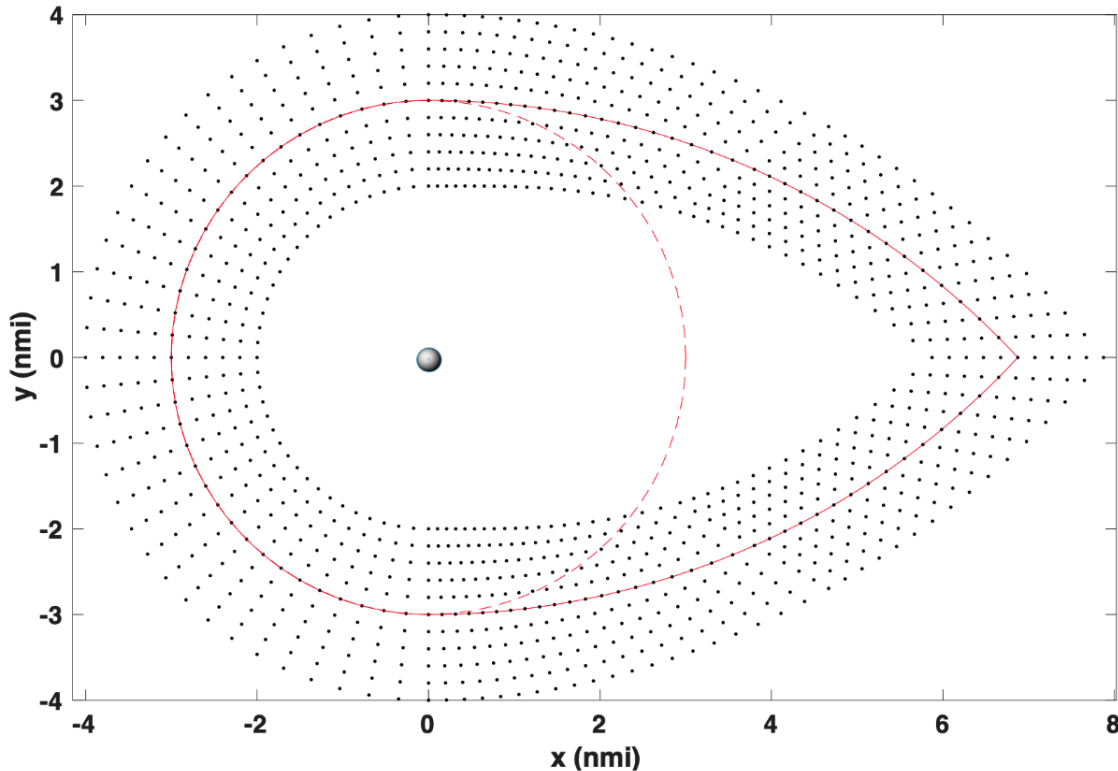


Sensitivity to the velocity





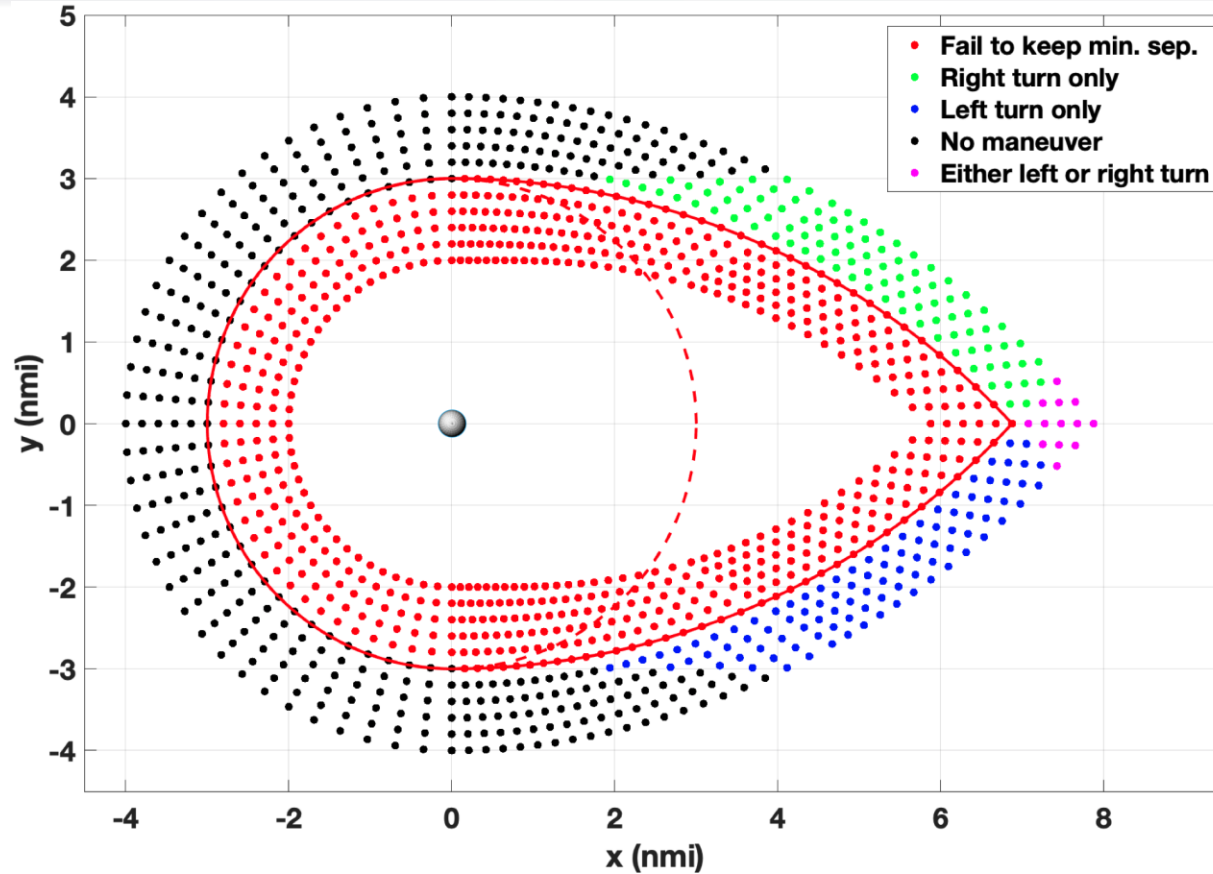
Simulation setup



- Put the Global Hawk at one grid point
- A total of 1,166 encounter cases
- Let the Global Hawk fly westbound
- Max. allowed bank angle = 14.8°
- Fe^3 traffic simulator^[2] is used:
 - Detect and avoid works @ 2Hz
 - Heading angle change only
 - Resolution with min. deviation
 - Kinetic trajectory model for the GH
 - Dynamic model for the balloon

[2] Xue et. al. , “ Fe^3 : An Evaluation Tool for Low-Altitude Air Traffic Operations”, AIAA Aviation Forum, 2018.

Simulation results





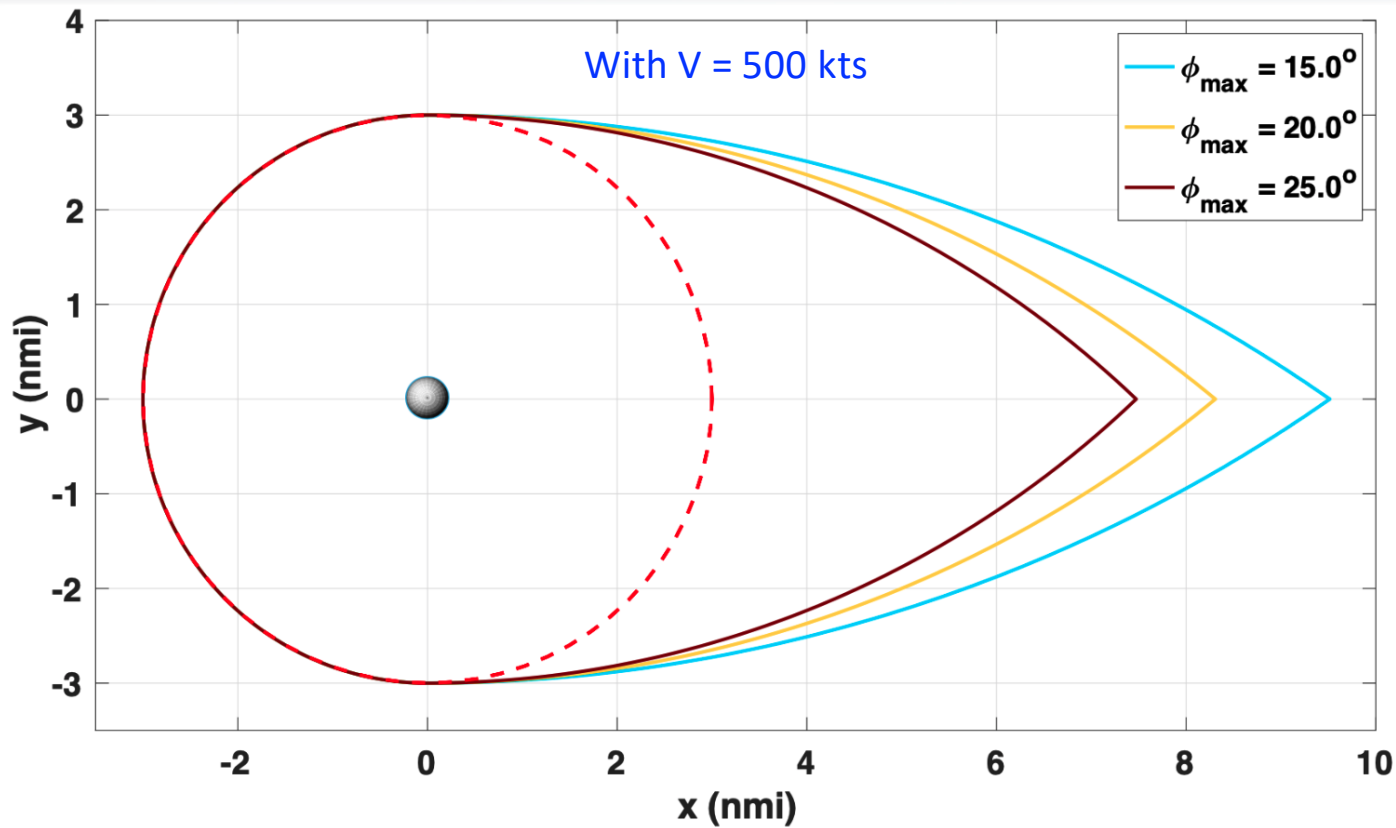
Main Contribution



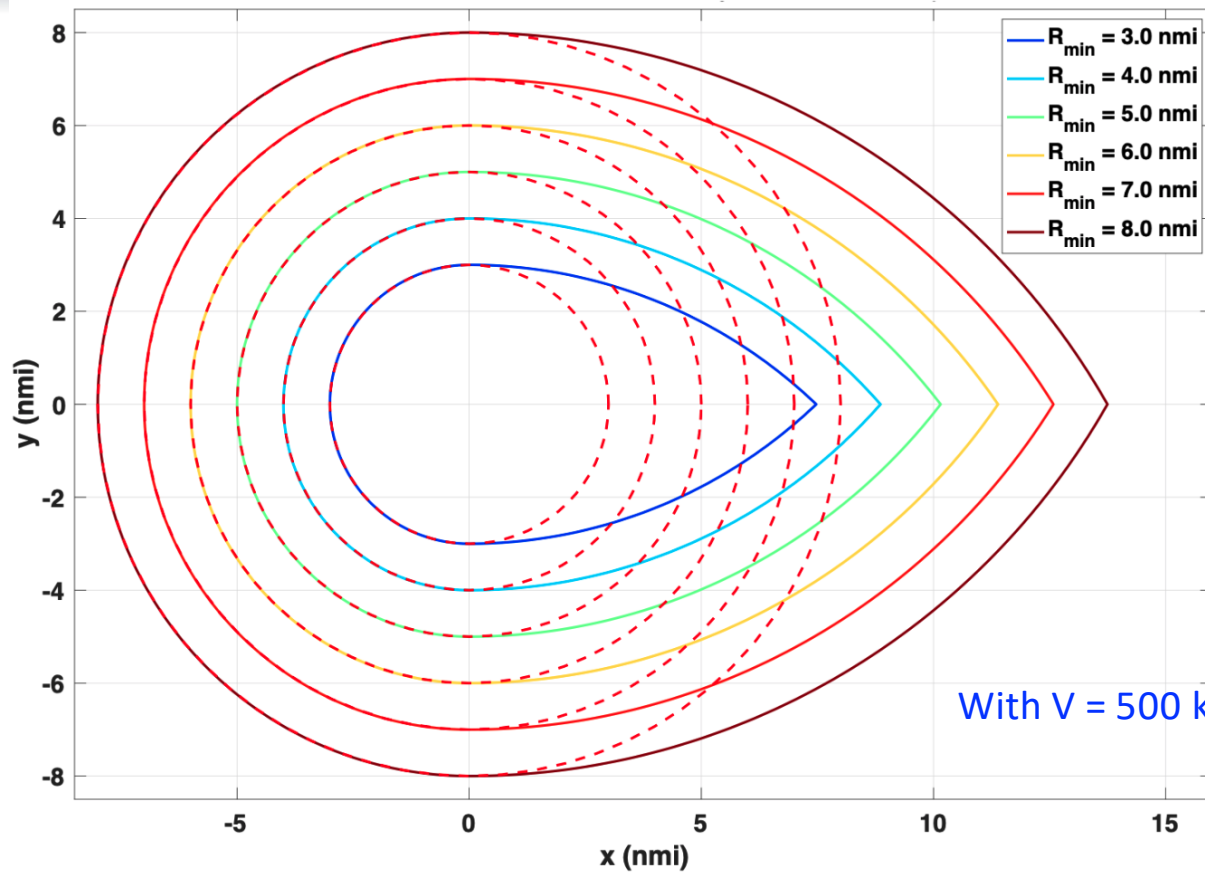
- An analytical method was developed to define the minimum safe operational boundary driven by maneuverability and delay.
 - Sensitivity analysis shows that the extra separation is dynamically decided by various parameters.
 - Simulation experiments with pairwise encounters verified the analytical results.
- This analytical method will be important to understand and define well-clear type of definition and advance the state of the art.
 - Define reference timelines for cooperative operation concept
 - Used as guidance for tactical avoidance for any pairwise encounter.



Sensitivity to the bank angle



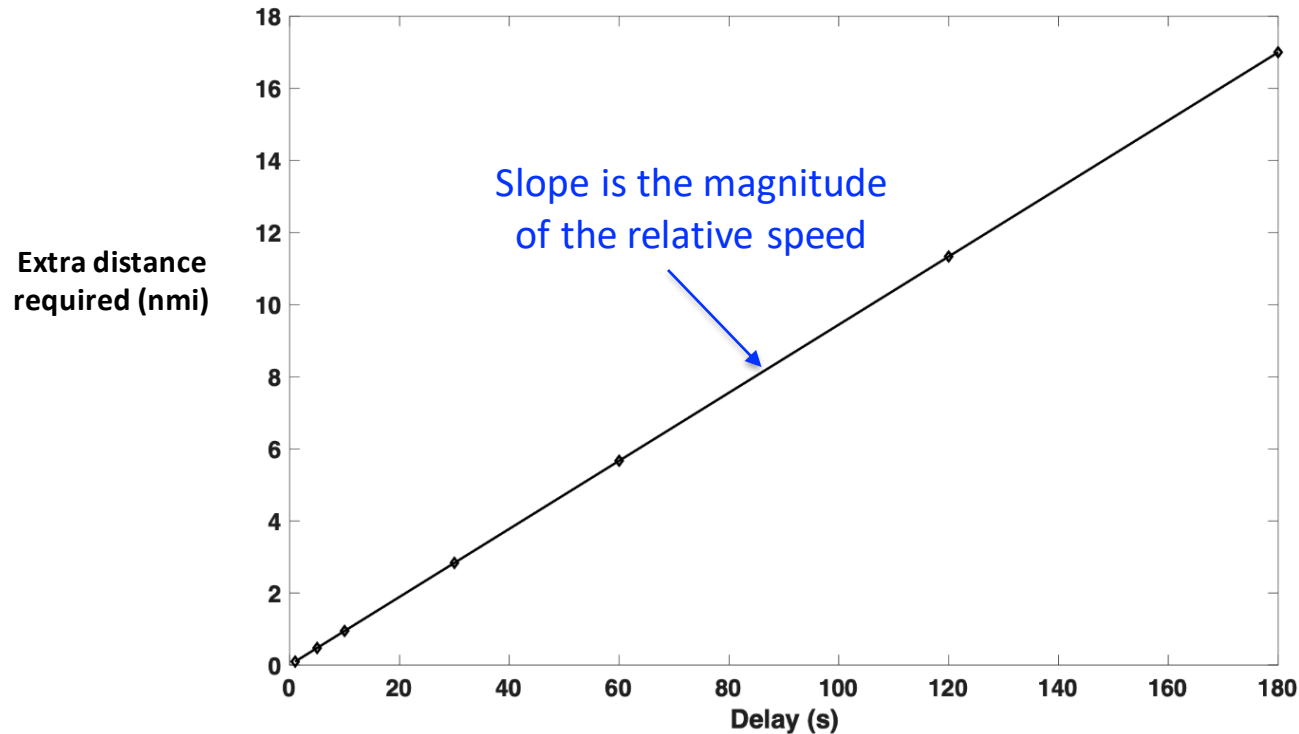
Sensitivity to $R_{\min}$



With $V = 500$ kts & 25° bank angle



Sensitivity to the delay caused by latency and control response



Global Hawk vs. static balloon