

A Concept of Operations for Power Beaming of Electric Air Vehicles

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NASA Ames Research Center

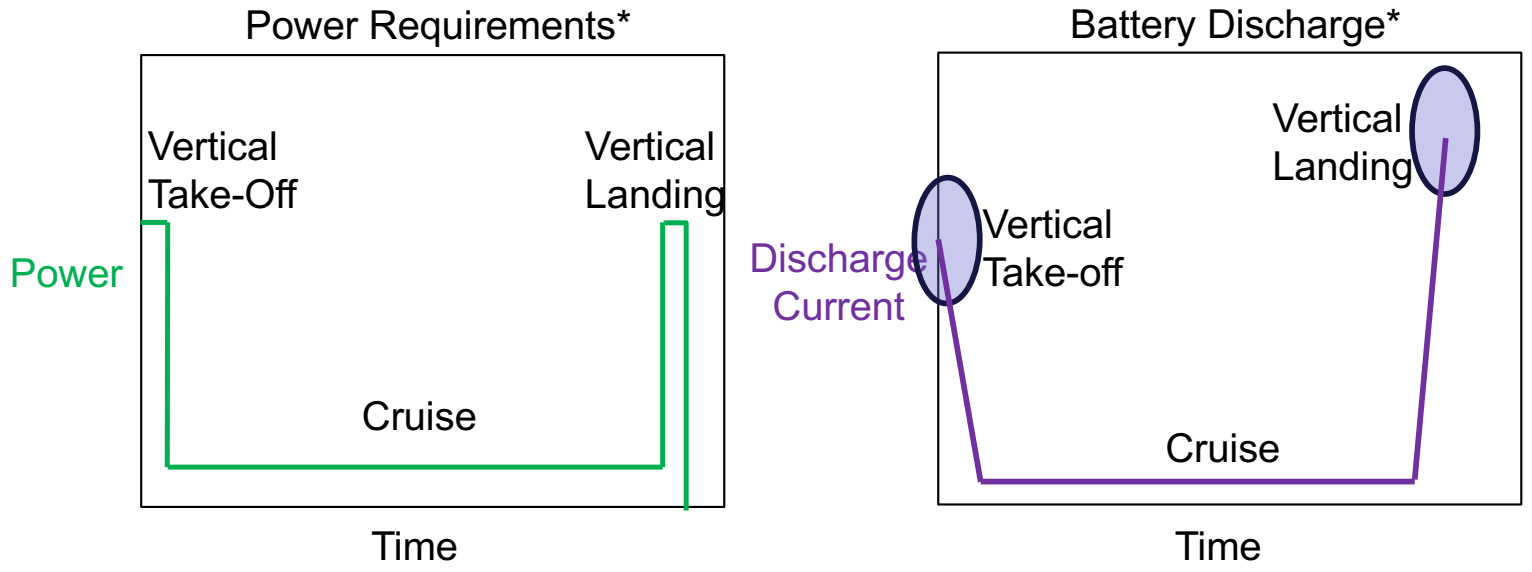
Robert Winsor
TacitEdge/DARPA

Hayden Klopp, Geoffrey Landis, Lee Kohlman, and David Pike
NASA Glenn Research Center

Presented at 2023 Digital Avionics Systems Conference
October 5, 2023

AAM† Vehicle Battery Use

- Planned operations and vehicle designs are limited by the power and the capacity of batteries
- Takeoff, landing, and reserves consume ~40% of available energy
- eVTOL§ takeoffs and landings require high power (~8 times horizontal flight), increasing safety risk
- Low energy or emergency landing (especially under extreme weather) uses even more energy and a severe threat to safe AAM operations

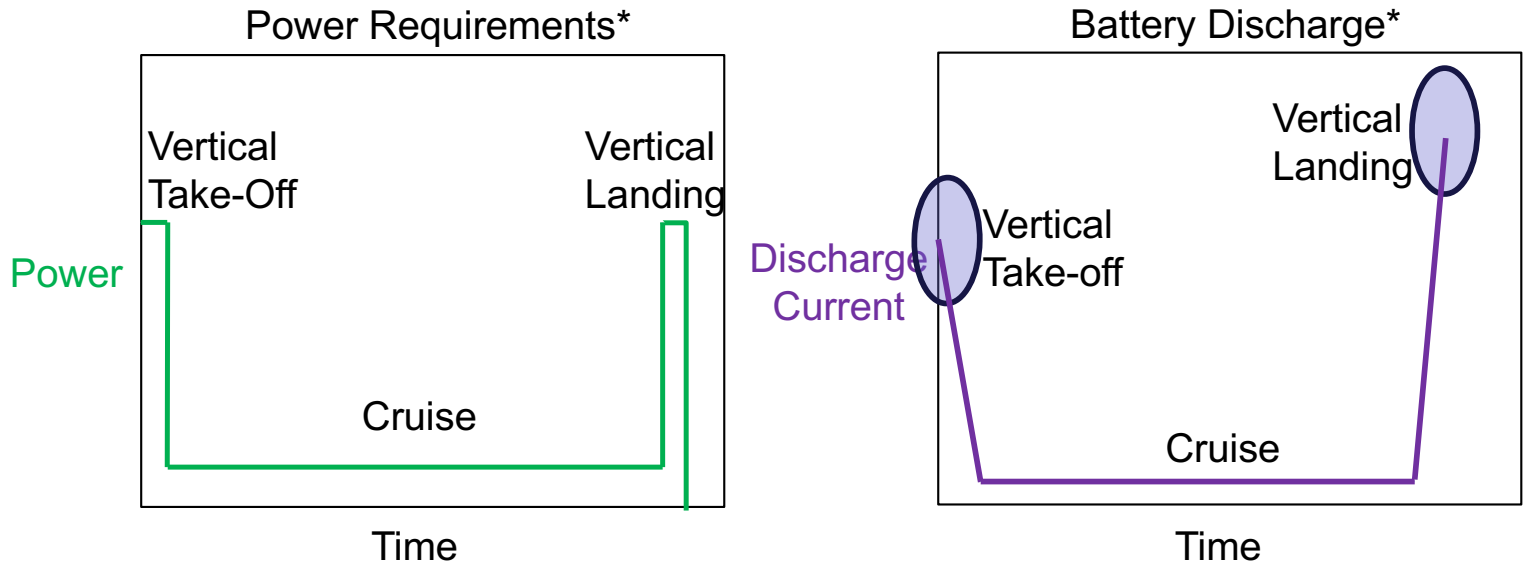


*W. L. Fredericks, et al., Performance Metrics Required of Next-Generation Batteries to Electrify Vertical Takeoff and Landing (VTOL) Aircraft (2018)

†AAM = Advanced Air Mobility, §eVTOL = electric Vertical Take-Off and Landing

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We developed a concept to recharge the battery with power beaming before the vehicle reaches its destination

†AAM = Advanced Air Mobility, §eVTOL = electric Vertical Take-Off and Landing

Outline

- Power beaming concept
- Parameter estimation
- Energy transmission efficiency
- Airspace constraint
- Future work
- Concluding remarks

Radio Frequency Power Beam

- Three Radio Frequency (RF) power beaming concepts*
  - Optical/Infrared (laser)
  - Millimeter Wave
  - Microwave

Characteristic Considerations	Optical	Millimeter Wave	Microwave
Penetration clouds/rain/fog	No	Poor	Excellent
Conversion efficiency Performance limits for DC-to-RF & RF-to-DC conversion	OK	OK	Good
Required Aperture Size Transmit and receive antenna sizes	Small	Medium	Large
Safety Due regard, pointing	OK	Good	Good
Economy of Scale Based on present state of the art to deliver 1000s of kW over 1000s of km	Poor	Poor	Good

- Advantages: Silent, invisible, no moving parts, reduces enroute power requirements and maintenance operations
- Disadvantages: Safety issues uncharacterized, RF spectrum availability and increase airspace complexity

*Rodenbeck, C.T., Jaffe, P.I., et al. "Microwave and Millimeter Wave Power Beaming," *IEEE Journal of Microwaves, Jan. 2021*

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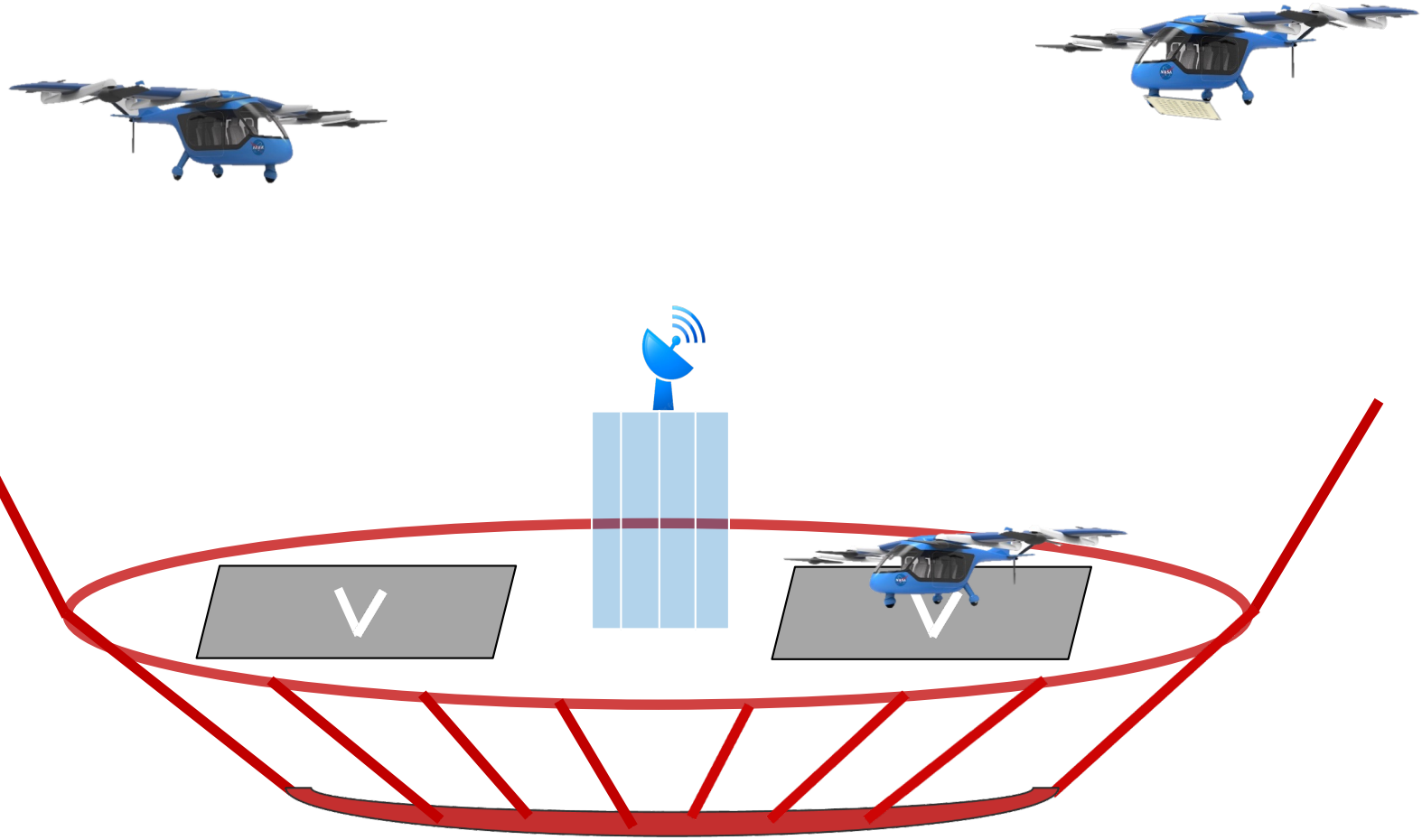
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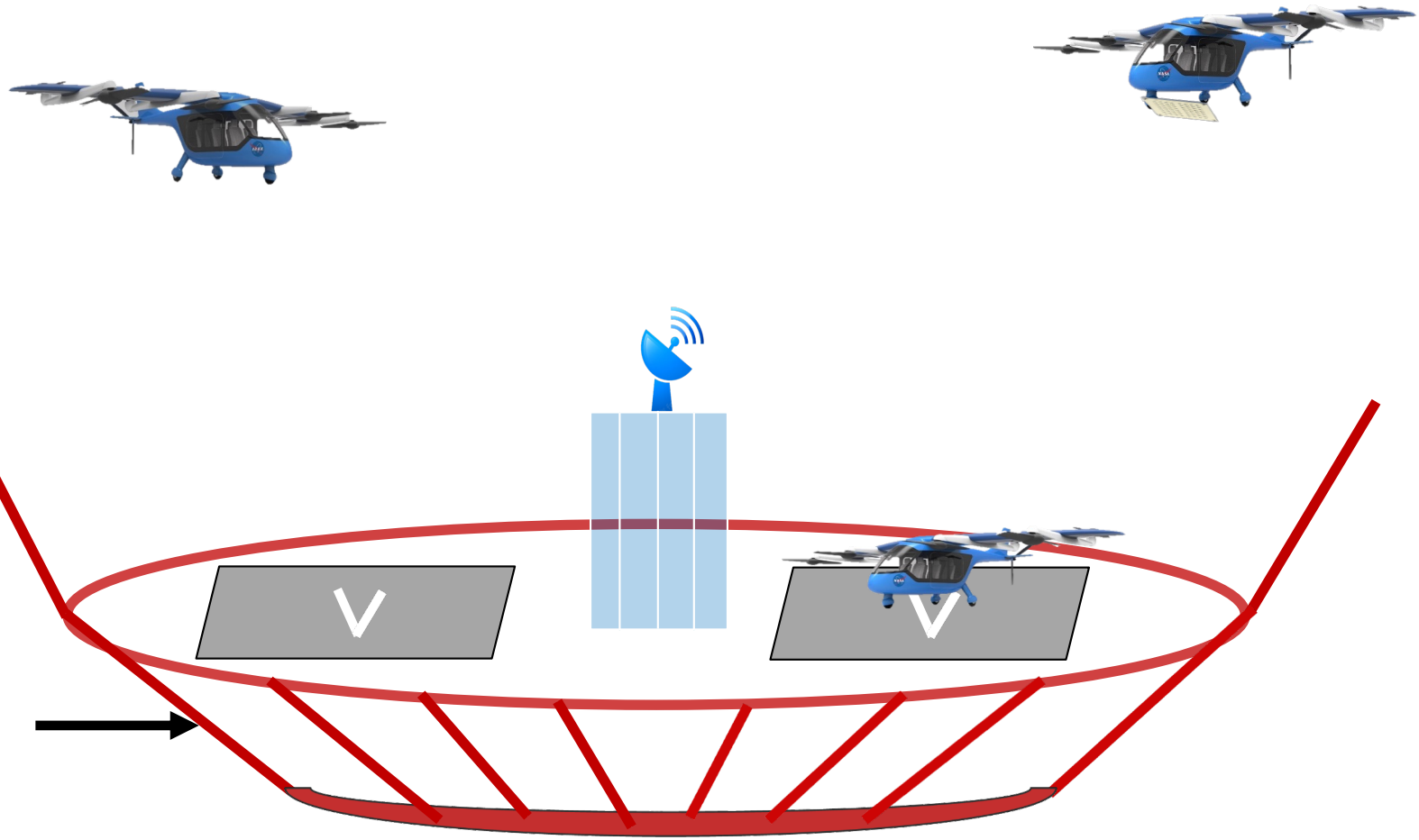
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Power Beaming Approach



Vehicle charging during hover while waiting to land at a vertiport and keeping the humans safe on-board

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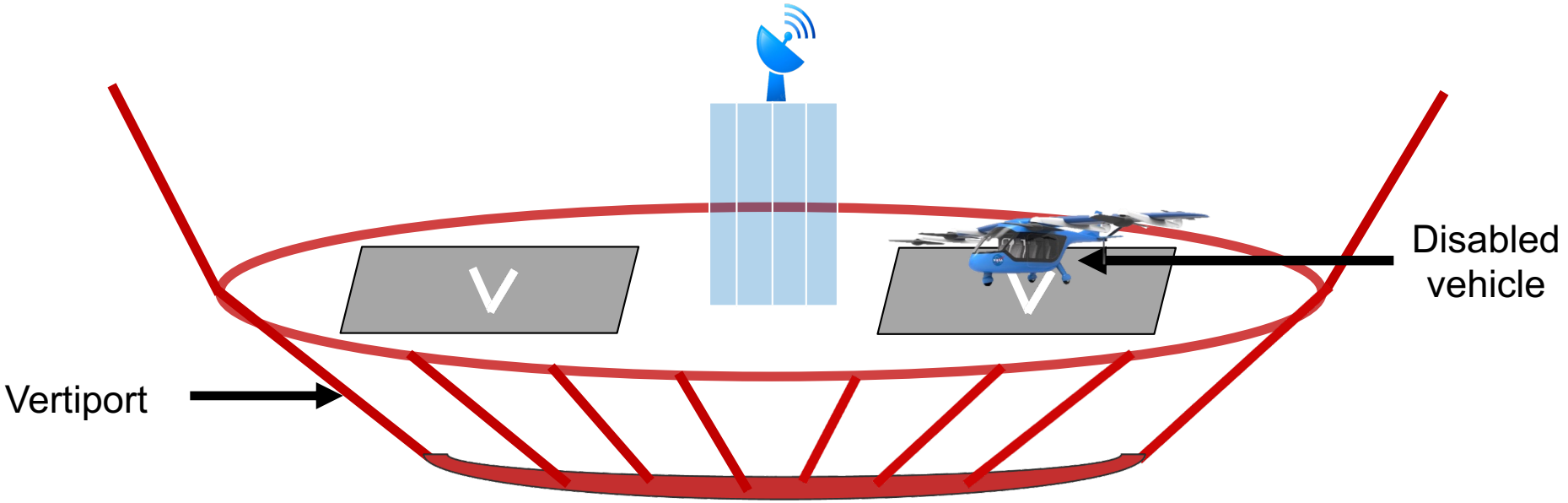


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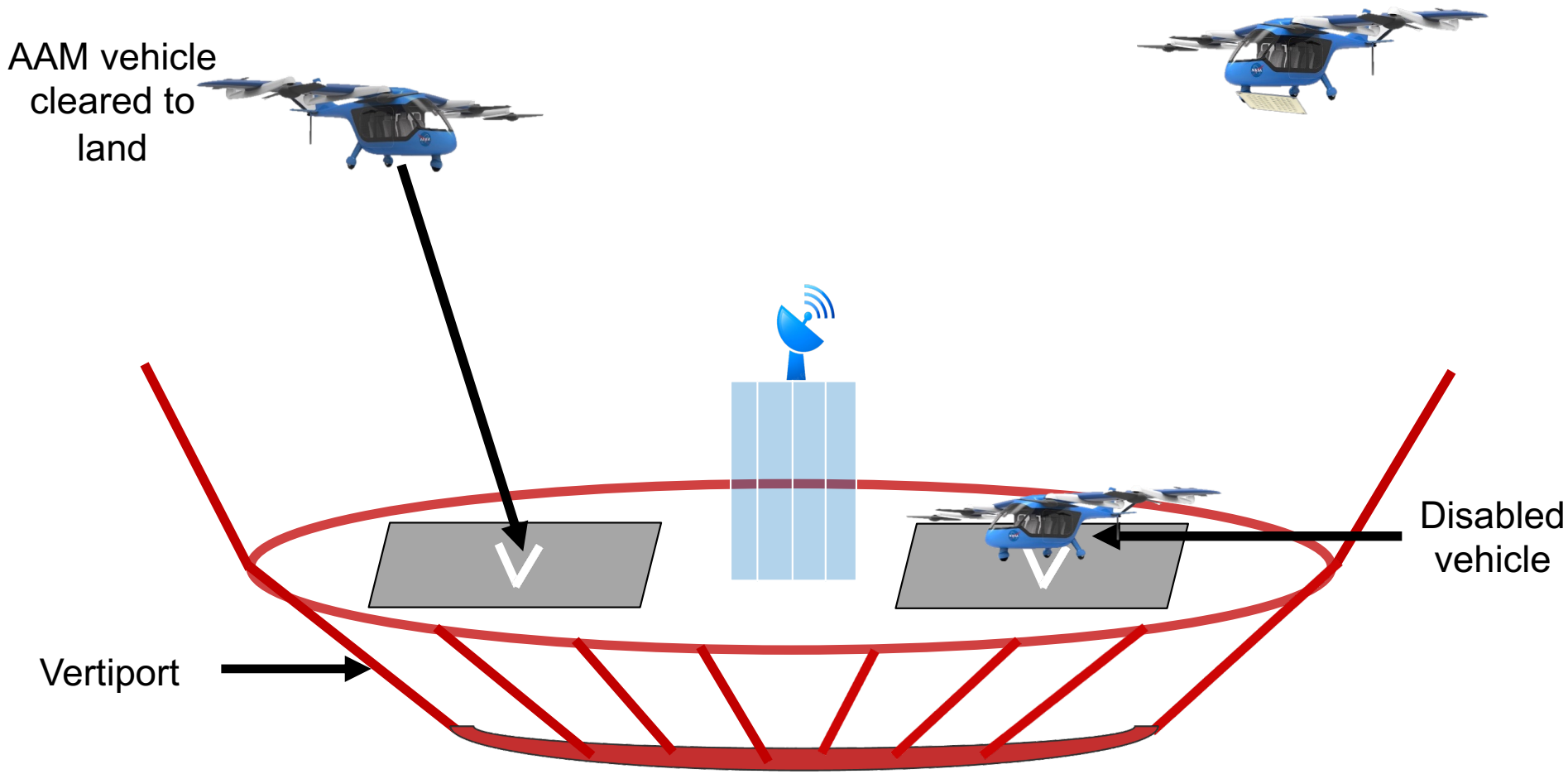






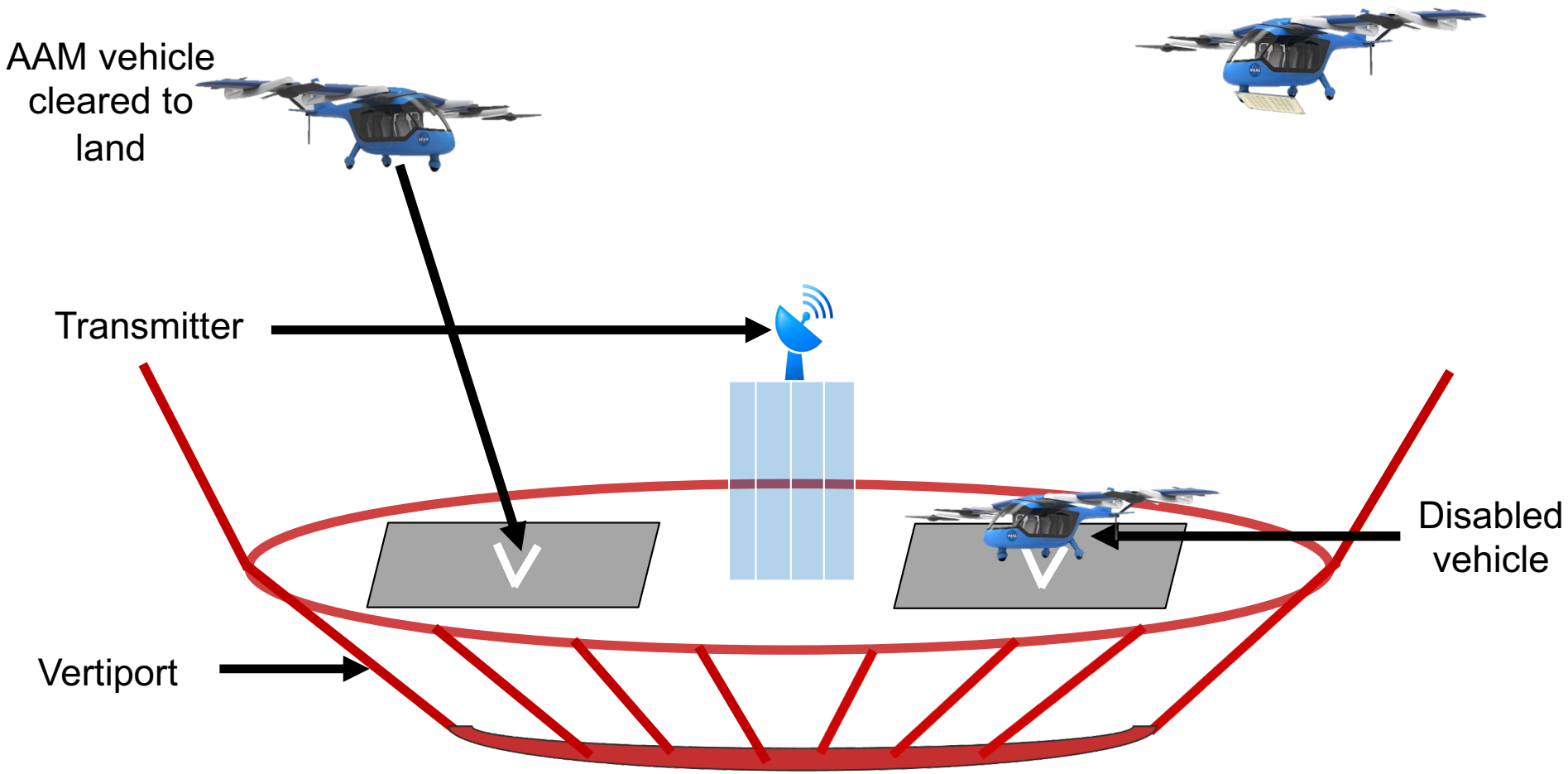
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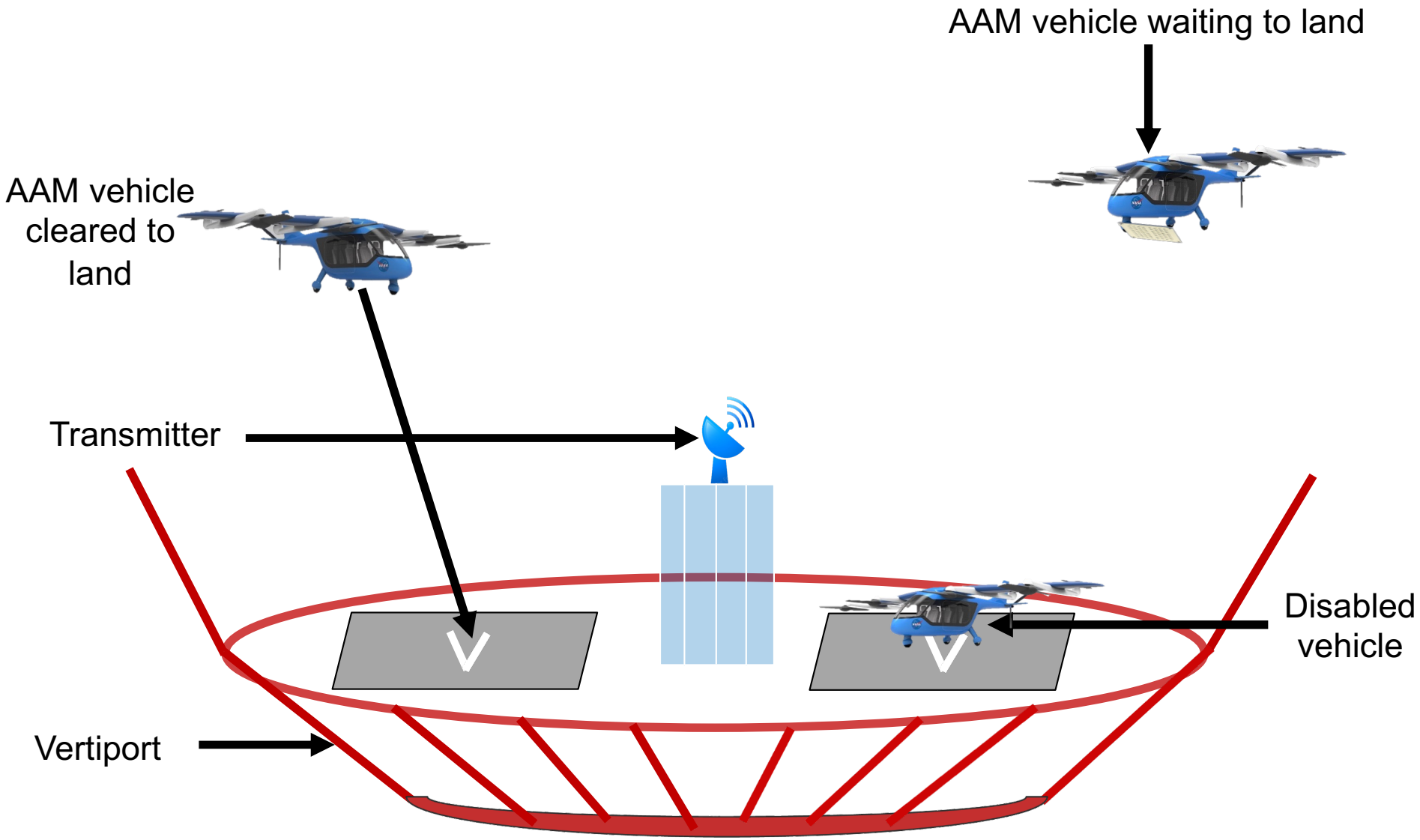
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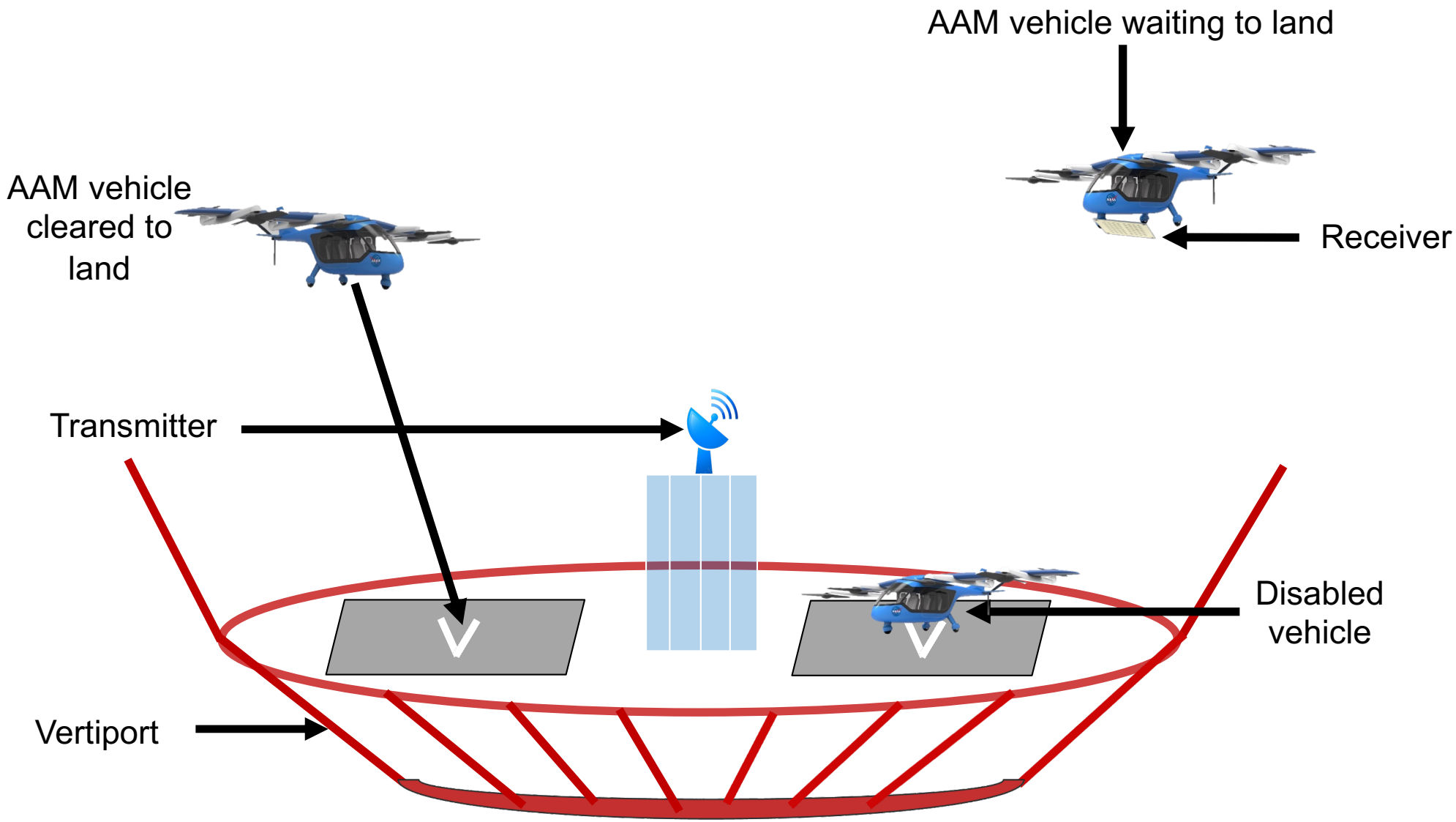
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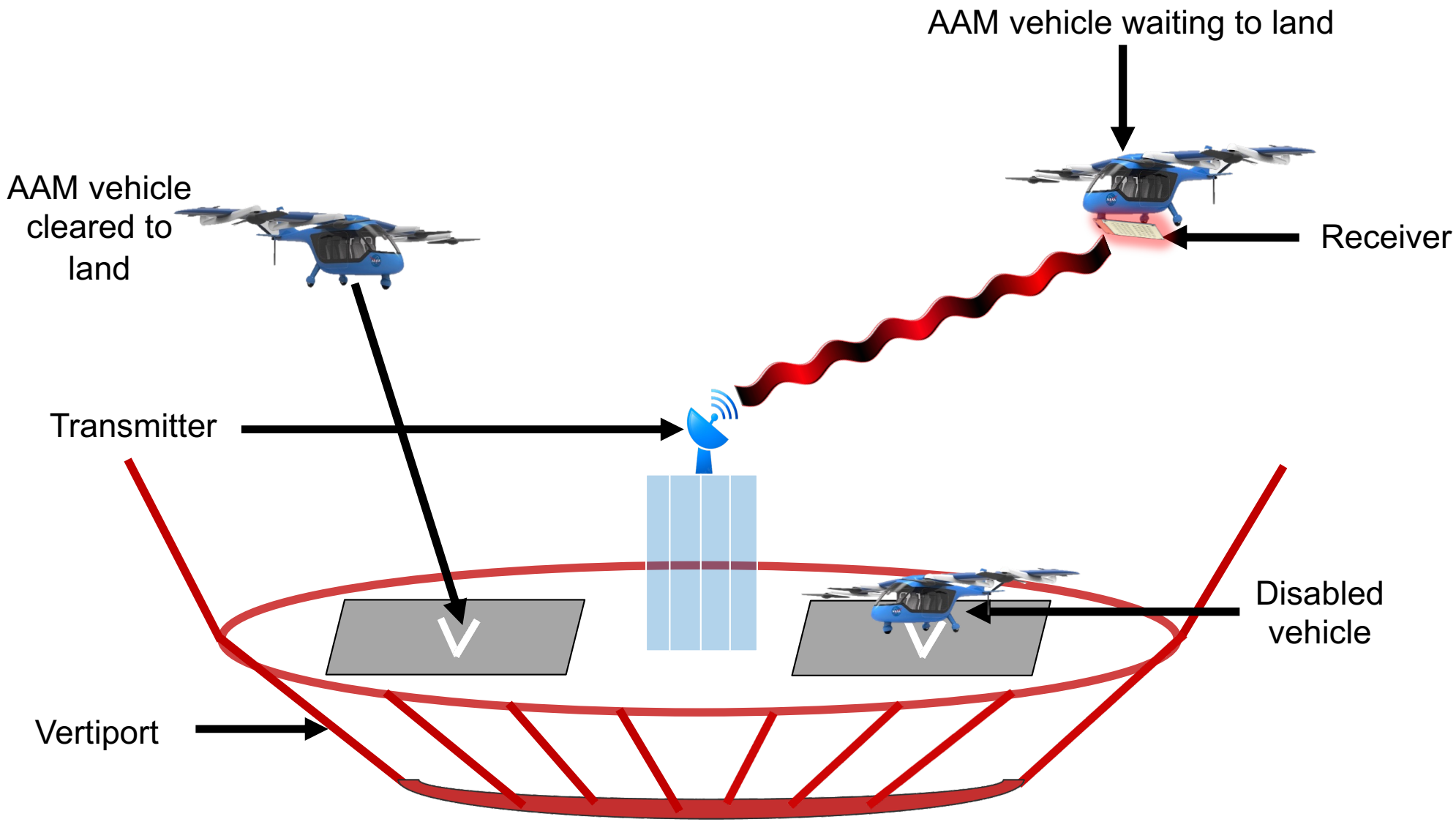
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Initial List of Parameters

Microwave Power Beam Setup (Transmitter, Receiver, Vehicle)

- †Antenna area = 9 m^2
- †Antenna transmit power = 2.5 kW

- Receiver antenna area
- Required electrical power
- Frequency of transmission
- Charging distance
- Beaming angle
- Beam width

†Wuschek, M., "Safety Distances at a Demonstration System for Wireless Power Transfer using Electromagnetic Waves." EM Institut, for Airbus Defense and Space GmbH, Regensburg, Germany, October 2022.

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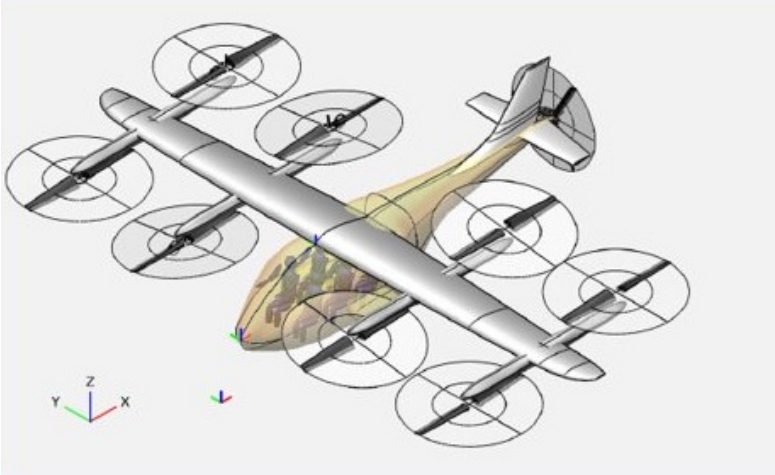
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- Target safety standard < 5 mW/cm^2
  - Power of transmitter
  - Distance from body
  - Time of exposure

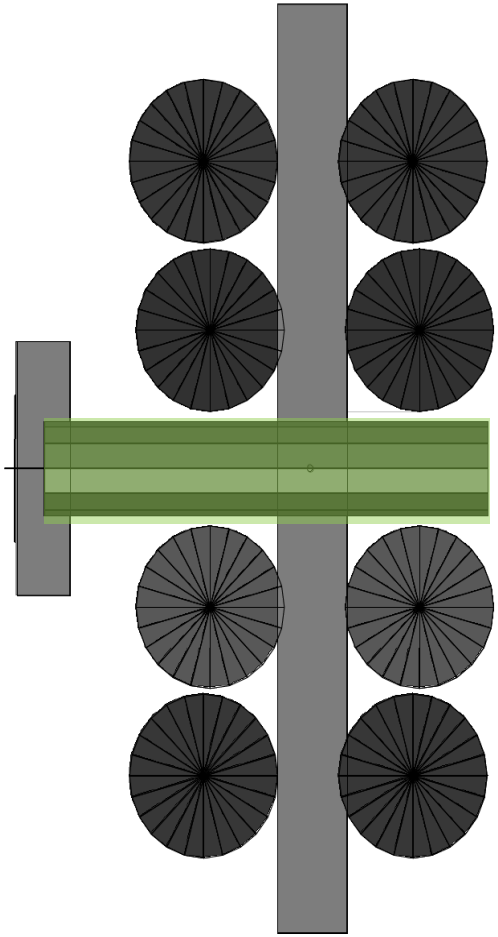
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Vehicle and Rectenna Parameters

Lift+Cruise†



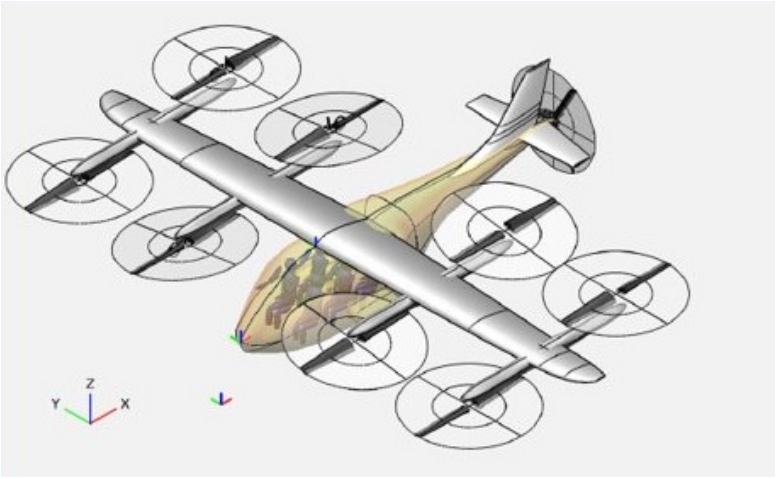
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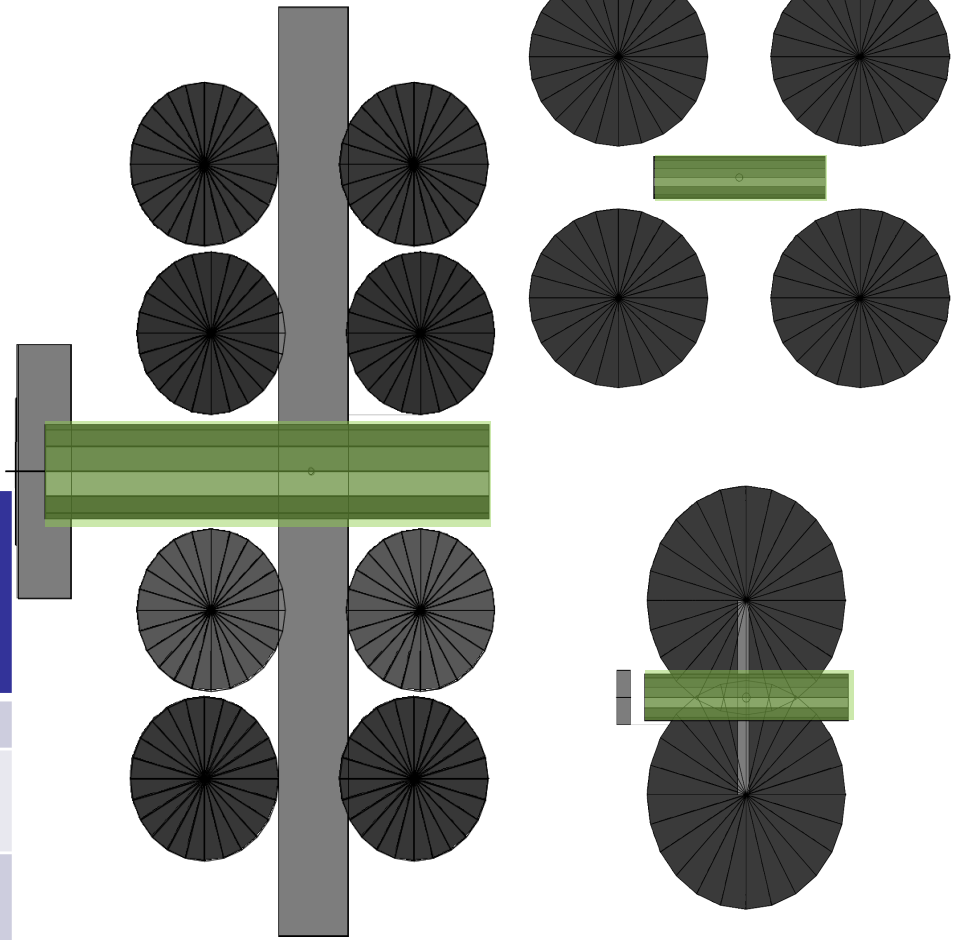
Lift+Cruise†



Model	DGW (lbs.)	Bottom Surface Area (m^2)	Hover Power (kW)	Cruise Power (kW)
Quadrotor	6480	9.5	345	263
Side-by-Side (SbS)	4897	11.3	290	150
Lift+Cruise (L+C)	8210	10.3	827	246

Lift+Cruise

Quadrotor

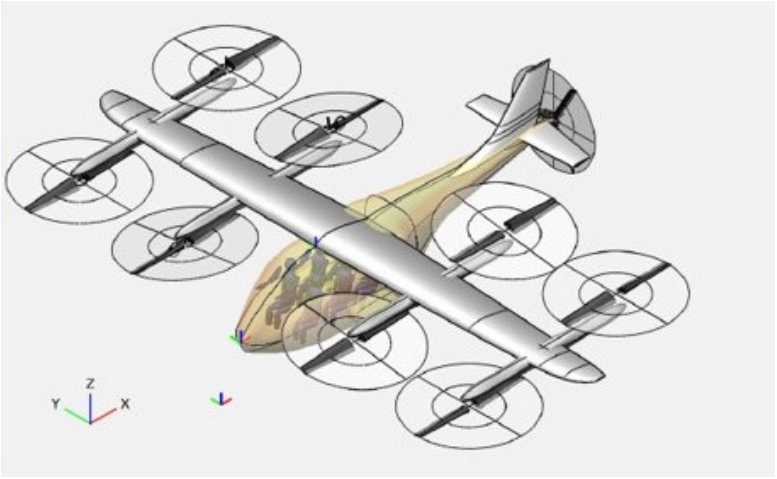


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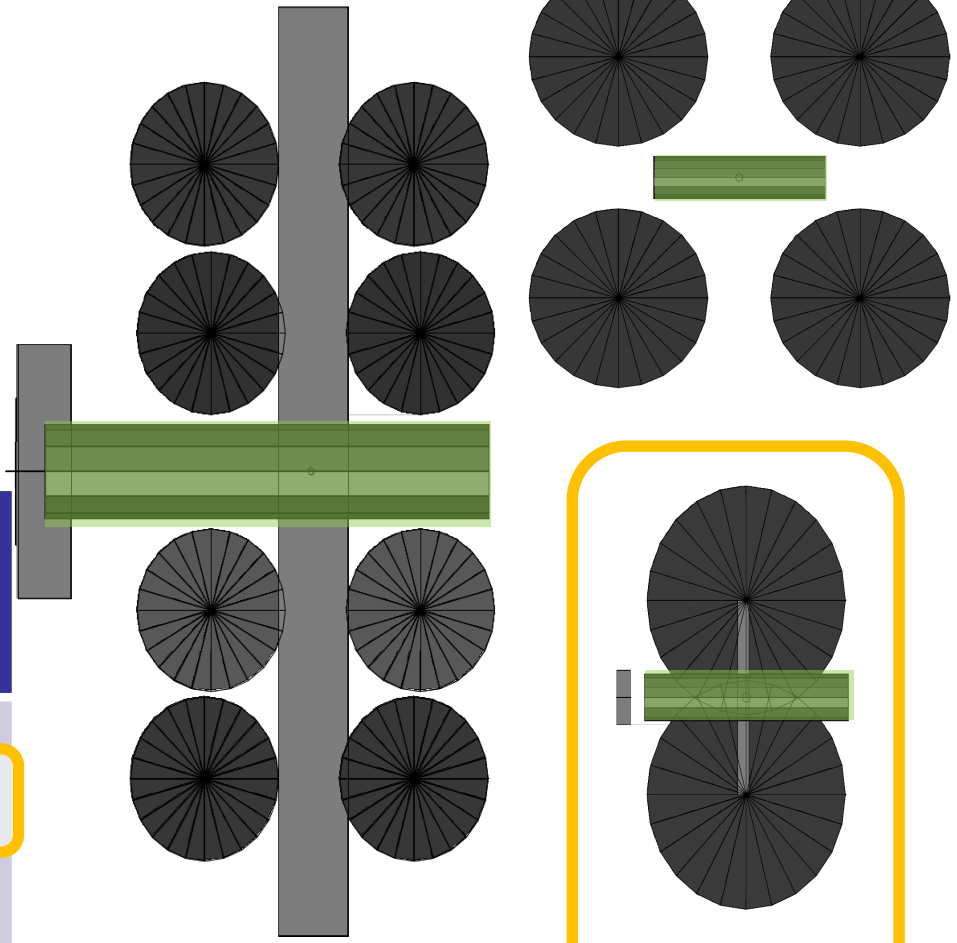
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Microwave Power Beam Setup (Transmitter, Receiver, Vehicle)

- Antenna area = 9 m^2
- Antenna transmit power: 2.5 kW

- Rectenna area = 11.3 m^2
- Required electrical power = 300 kW

- Frequency of transmission
- Charging distance
- Beaming angle
- Beam width

- Target safety standard < 5 mW/cm^2

Outline

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Frequency and Collection Efficiency

Rectenna Area: A_r = 11.3 m^2

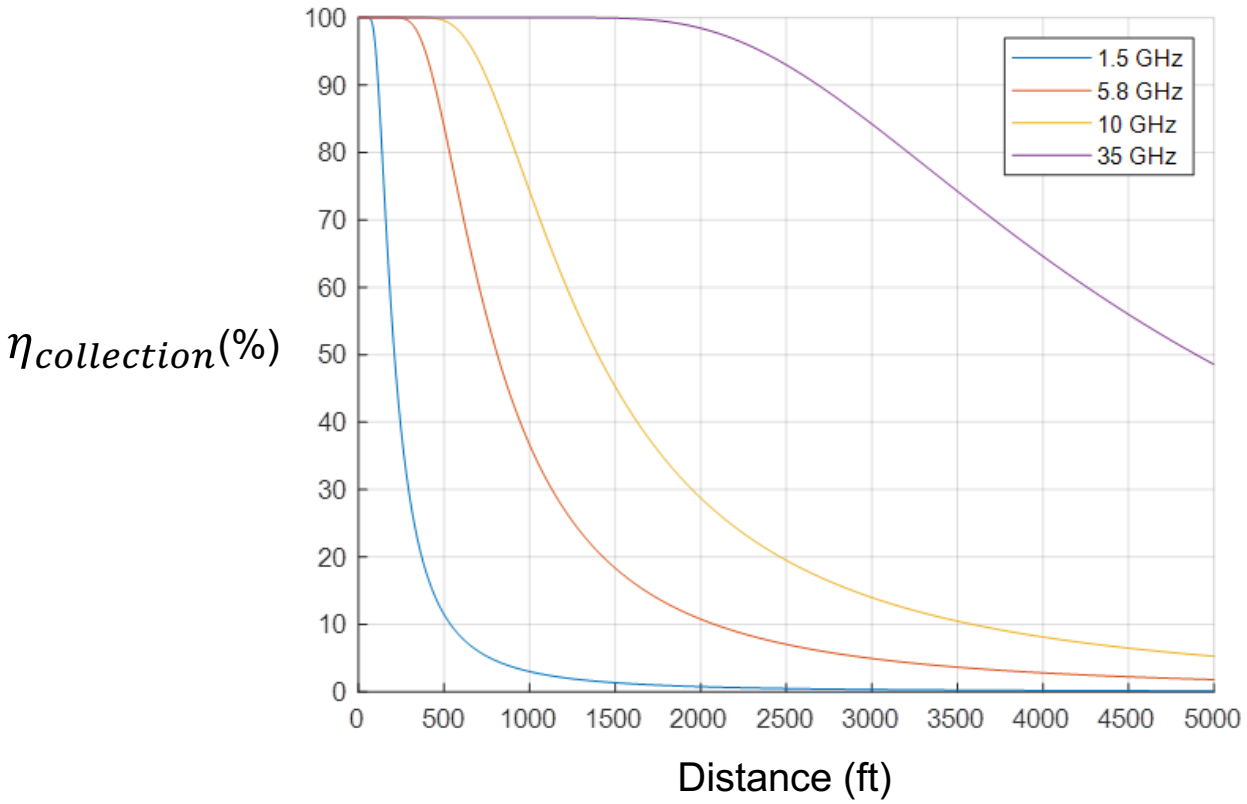
Transmitter Area: A_t = 9 m^2

Frequency: f = 1.5, 5.8, 10, 35 GHz

Wavelength = 20, 5.17, 3, 0.85 cm

$$\eta_{collection} = \frac{P_r}{P_t} = 1 - e^{-\tau^2}, where$$

$$\tau^2 = A_t A_r / (\lambda D)^2$$



Below 500 ft, rotor downwash and ground effects interfere with the charging process

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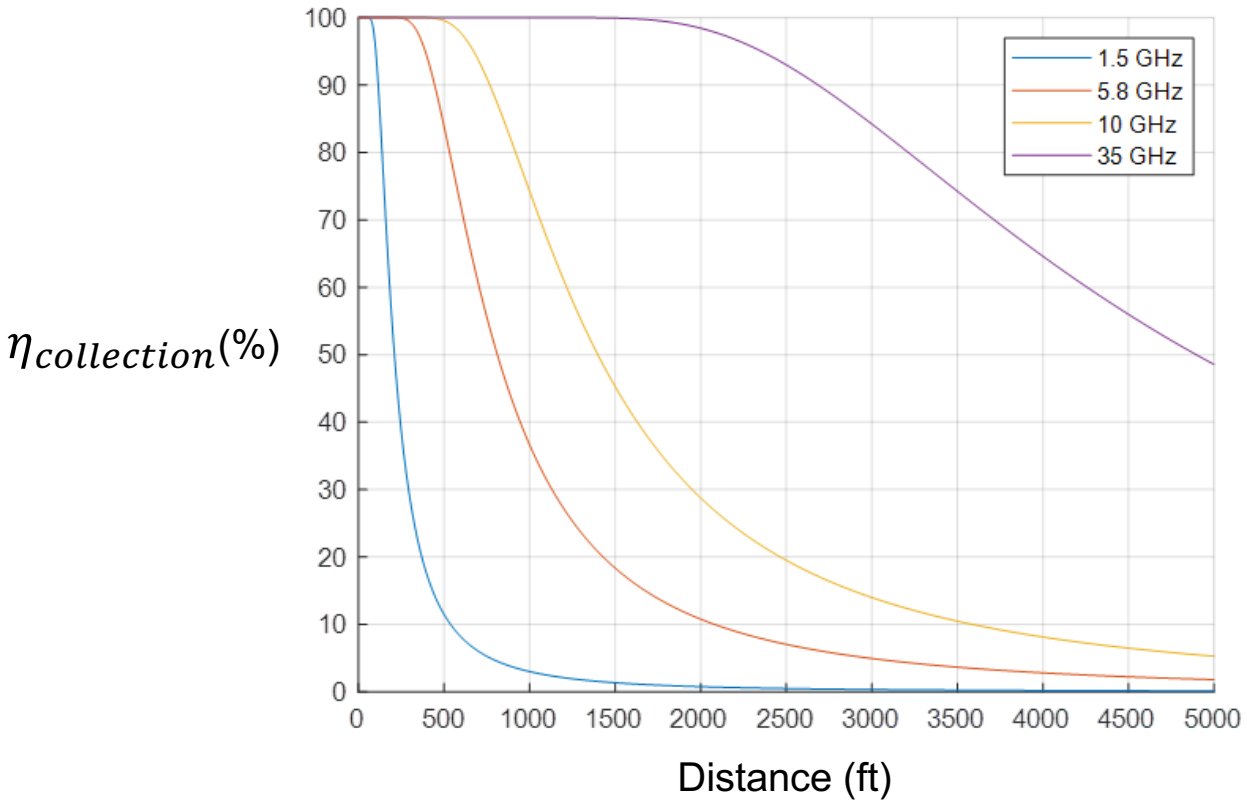
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Higher frequencies have better collection efficiency but perform poorly in weather

Combined Efficiency for 5.8 GHz

The best-case RF-to-DC conversion efficiency that can be achieved is 85%. The combined efficiency, $\eta_{combined}$, is defined as:

$$\eta_{combined} = \eta_{collection} * 0.85 * \sin(\ Angle\ )$$

Distance	100 ft	500 ft	1000 ft	1500 ft	2000 ft	2500 ft	5000 ft
90° *Angle*	85%	59%	22%	10%	6 %	4%	1%
45° *Angle*	60%	42%	15%	7%	4%	3%	1%
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To justify the extra safety precautions, currently, a minimum combined efficiency of 50% is set as a requirement†.

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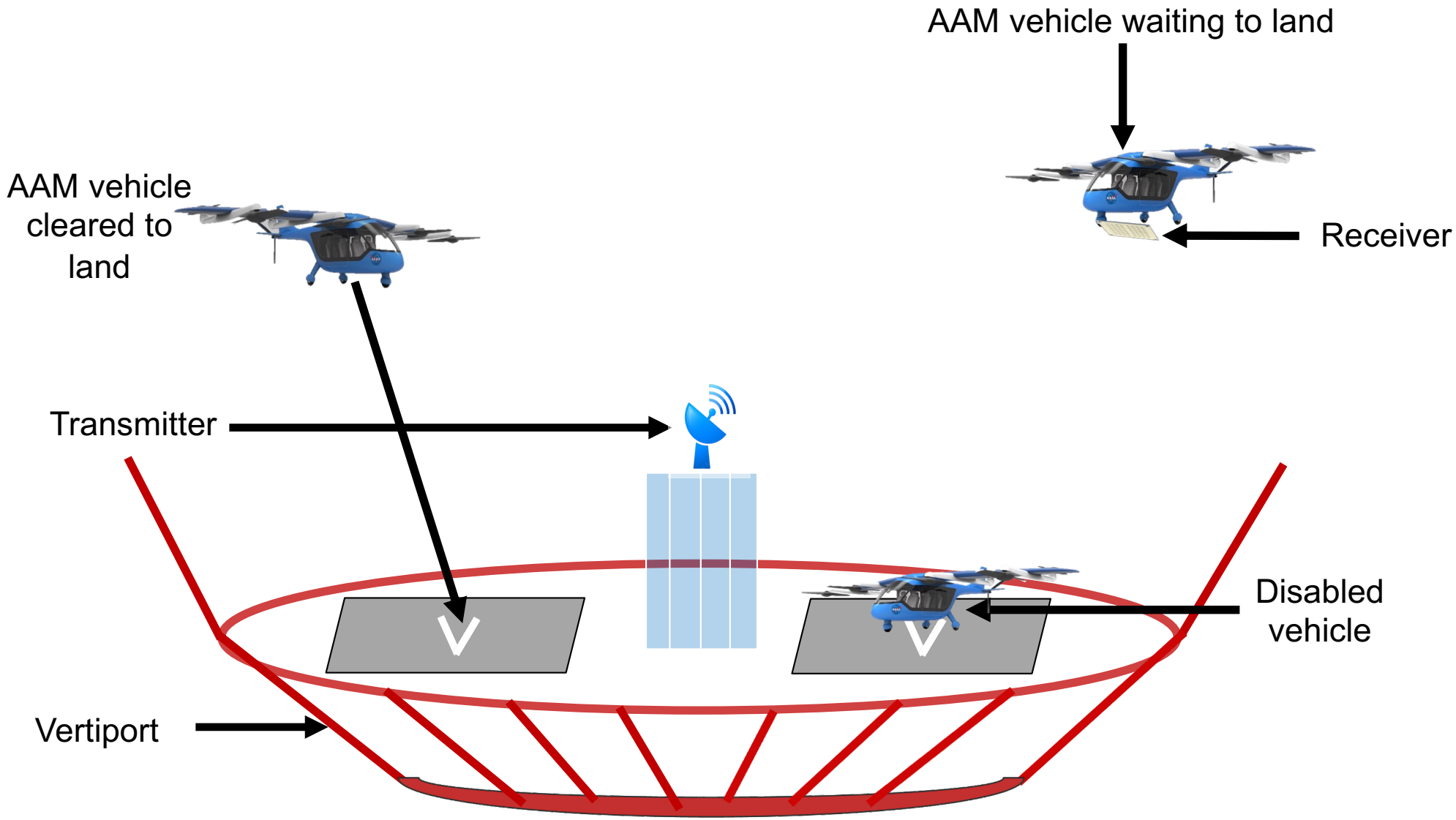
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- Required electrical power: 300 kW

- Frequency of transmission = 5.8 GHz
- Charging distance = 500 ft
- Beaming angle = 90˚

- Beam width

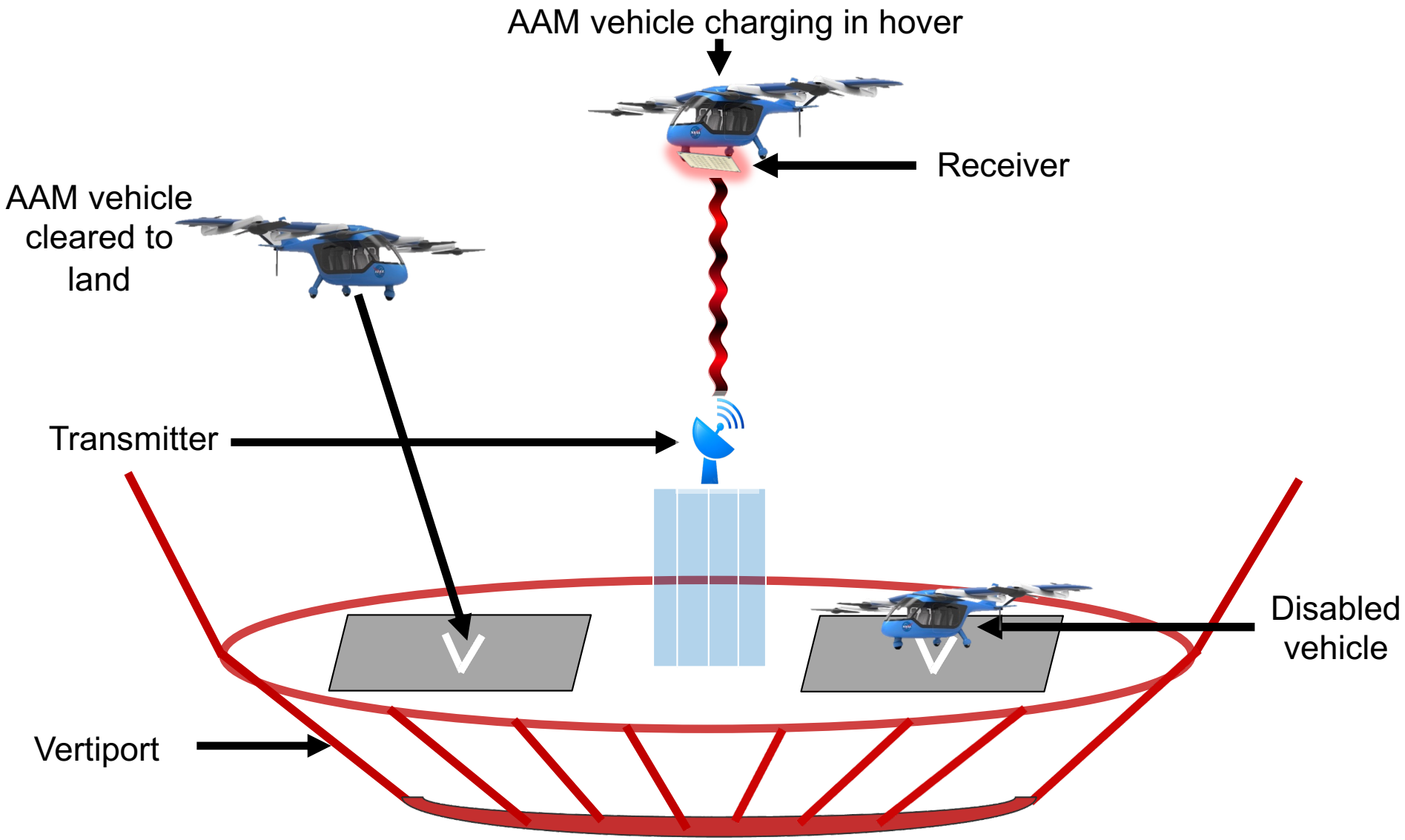
- Target safety standard < 5 mW/cm^2

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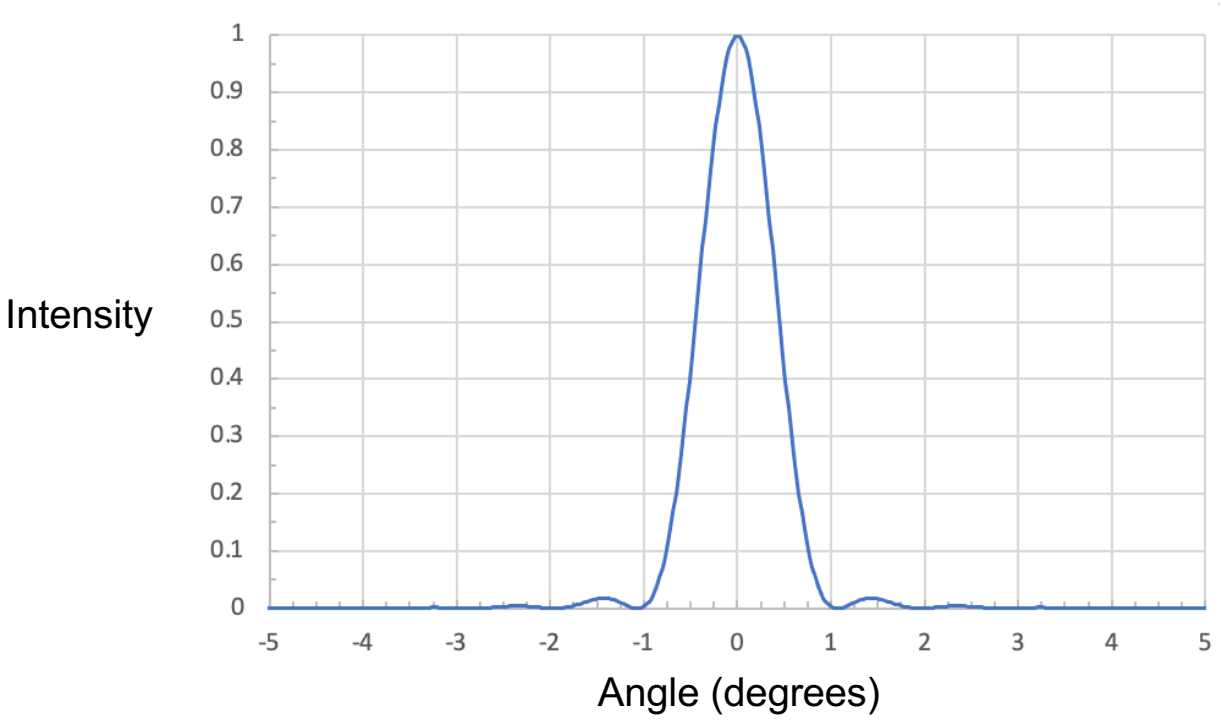
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Beam Width and Sidelobes

Rectenna Radius: r_t = 1.64 m, Wavelength: λ = 5.17 cm (f = 5.8 GHz)

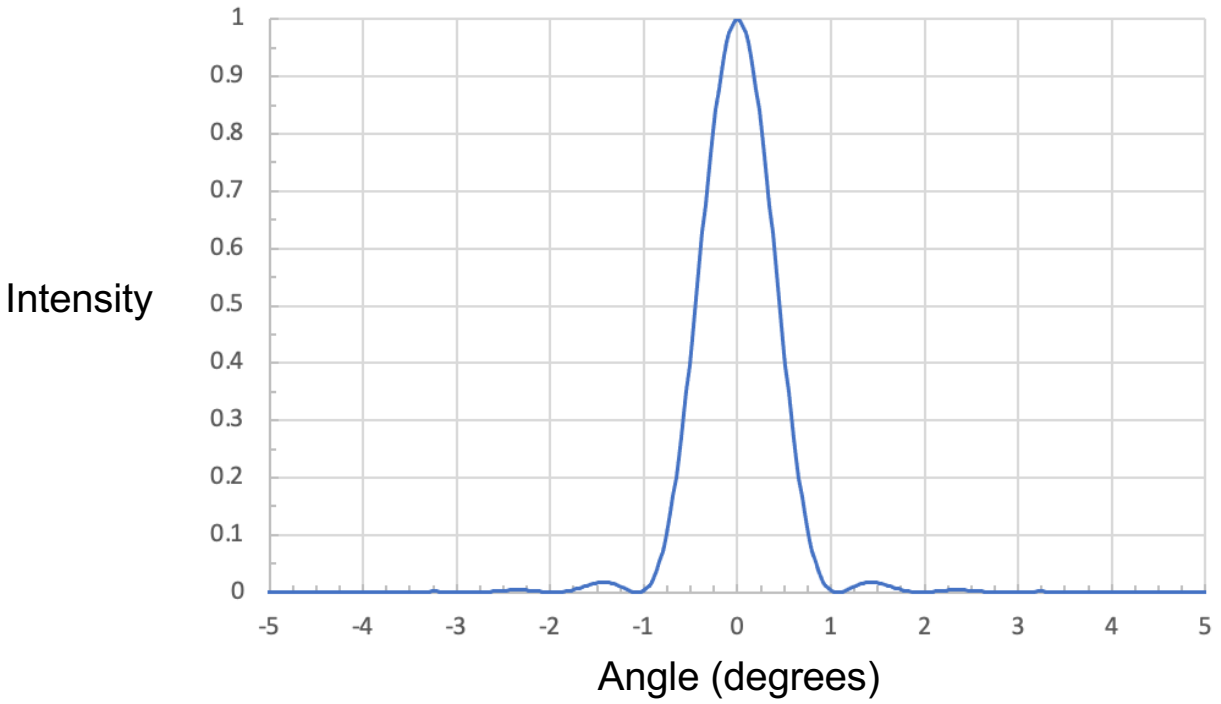
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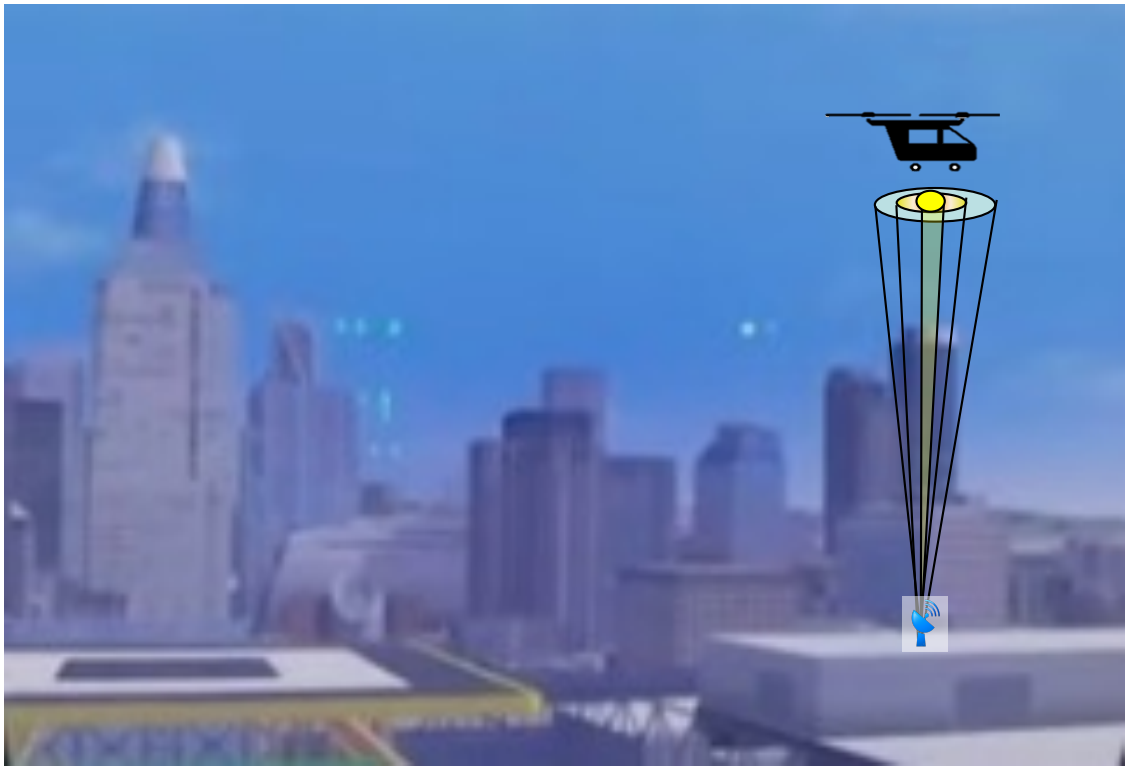
The central beam-half-angle is 1.1˚ but sidelobes could exist on either side up to 5˚ from the centerline

Imposed Airspace Constraint

The width of beam, w is defined as:

$$w = 2 * D * \tan(\theta_{central})$$

Based on D = 500 ft and using half-angle $\theta_{central}$ of 10˚ to accommodate the fringes of the beam, w is ~200 ft.

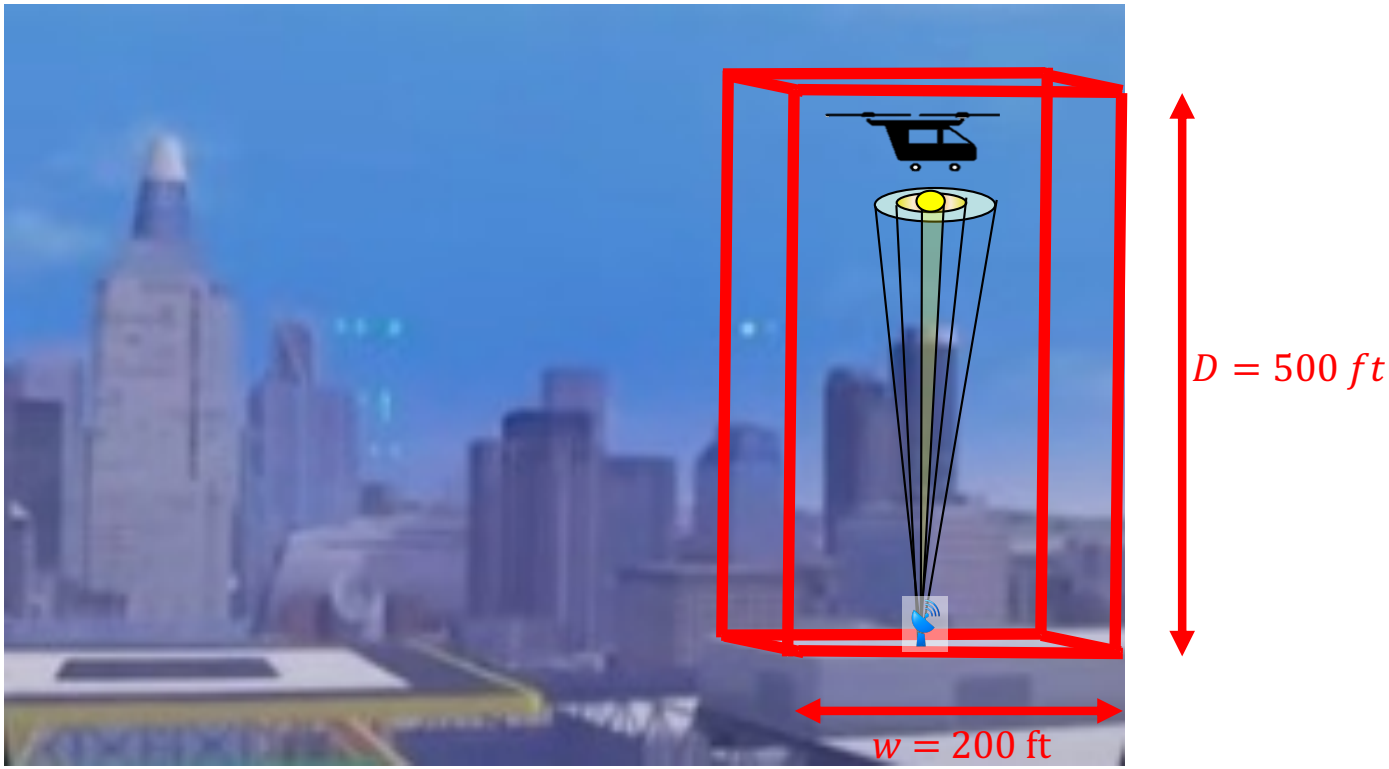


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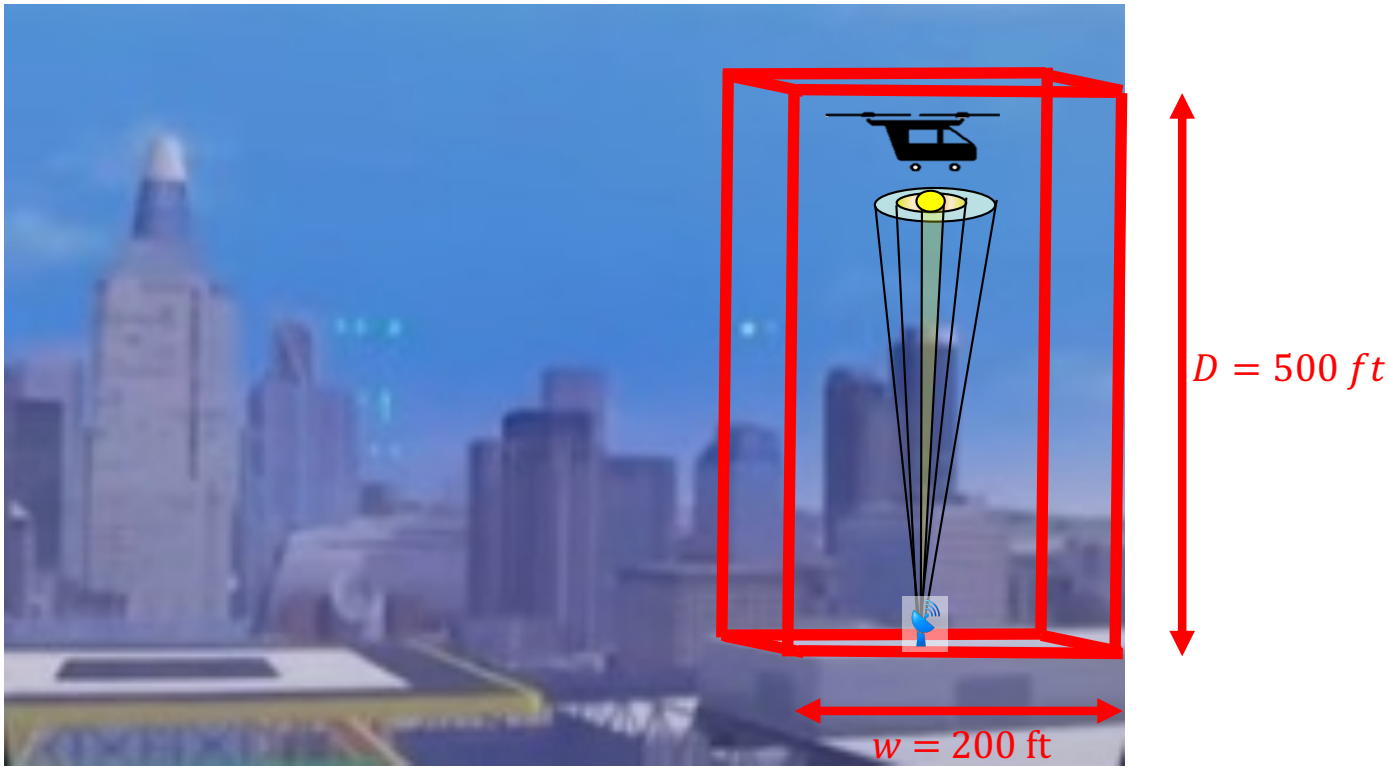


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The blocked airspace could be a Temporary Flight Restriction (TFR) or a Special Use Airspace (SUA) depending on regularity of the charging process

Resultant Parameters

Microwave Power Beam Setup

- Vehicle = Side-by-Side
- Required electrical power = 300 kW
- Rectenna area = 11.3 m^2

- Antenna area = 9 m^2
- Frequency of transmission = 5.8 GHz
- Antenna transmit power = 2.5 kW

- Charge distance = 500 ft
- Beaming angle = 90˚

- Beam width = 10˚
- Minimum TFR/SUA blockage = 500 ft x 200 ft x 200 ft

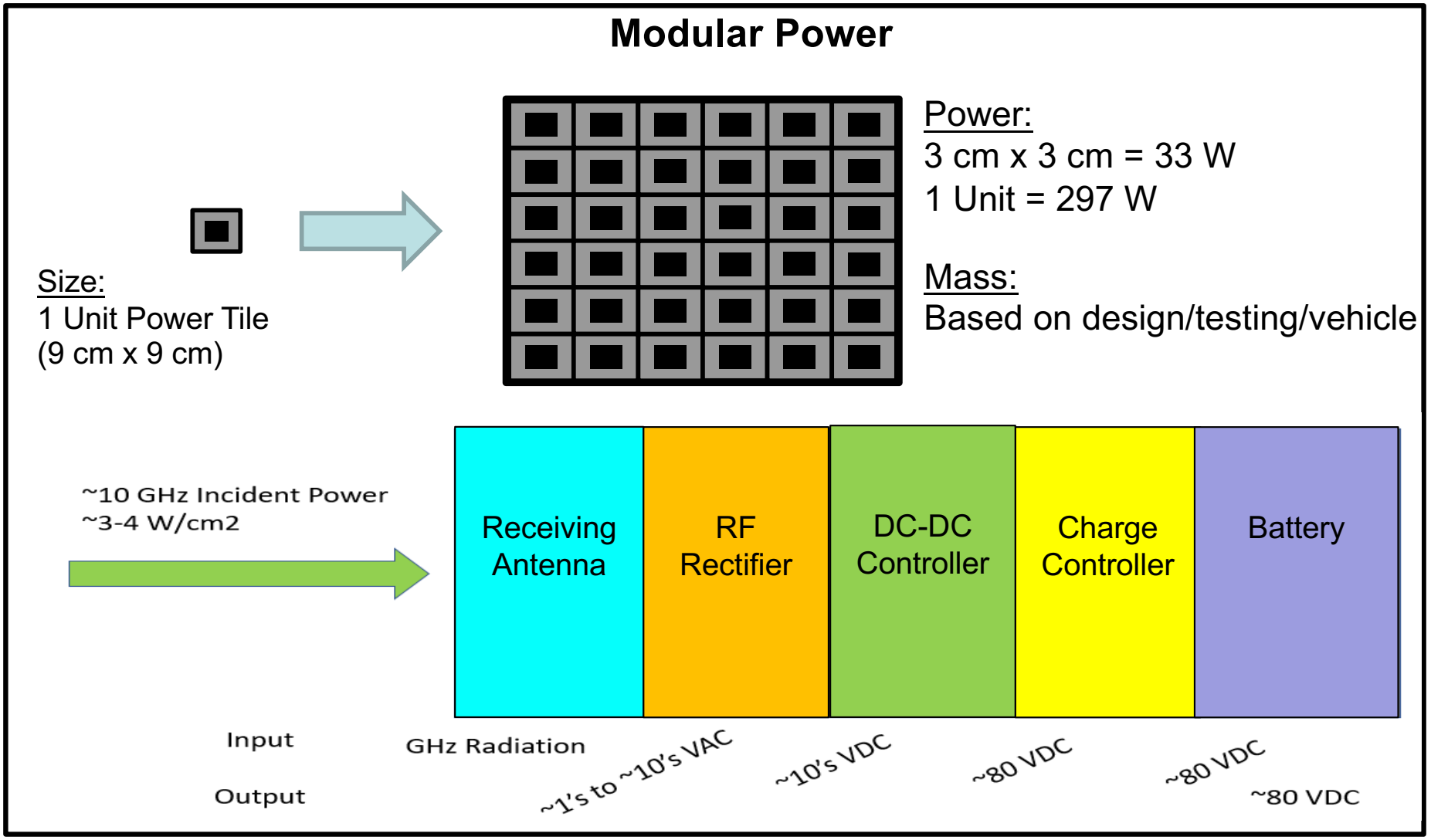
- Target safety standard < 5 mW/cm^2
  - Power of transmitter (2.5 kW)
  - Distance from body (500 ft)
  - Time of exposure (6 minutes)

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Future Work

- Power Tile Design and Performance



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- Test Chamber (Glenn Research Center)



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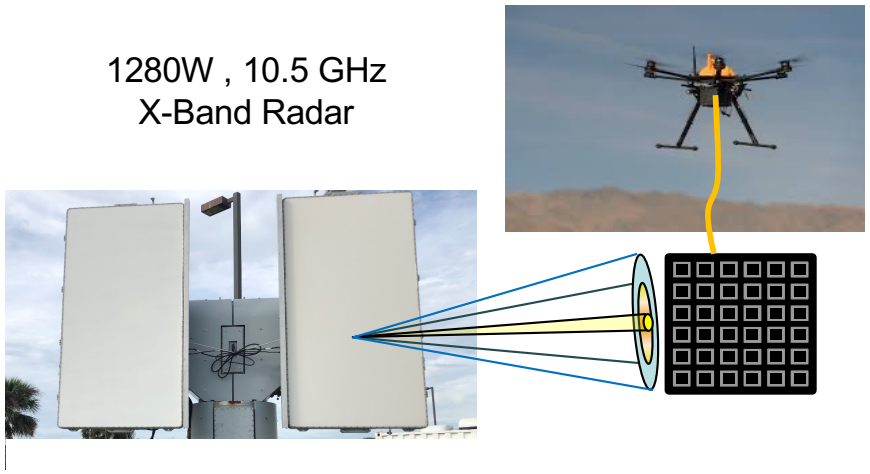
- Power Tile Design and Performance
- Test Chamber (Glenn Research Center)
- Transmitter and Test Range (Wallops Flight Facility)



Maps Data: Google, ©2023, Maxar Technologies

Future Work

- Power Tile Design and Performance
- Test Chamber (Glenn Research Center)
- Transmitter and Test Range (Wallops Flight Facility)
- Dynamic Test (Drone)



Concluding Remarks

- Insufficient battery charge is a key safety risk
- Safety of passengers is a critical factor to assess with this study
- Parameters for the concept of charging presented
- Intensity of beam allows the charging of vehicle in hover
- Spread of microwave beam is important in determining the airspace constraint
- Next phase of research to conduct the experiments

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Questions?

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