A Concept of Operations for Power Beaming of Electric Air Vehicles

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***Abstract*—A concept of operations is presented for power beaming of microwaves to extend battery charge of an electric air vehicle. Critical aspects of airspace operations and power beam charging are addressed. Three classes of electric Vertical Take-Off and Landing vehicle models are considered for recharging. The effects of transmitter frequency, antenna size, and beam width are analyzed. Based on past experiments in the industry, a 2.5 kW power beam is selected. A no-drag rectifying antenna under the belly of the vehicle is selected along with the conversion efficiency, power density, and its size. The combined efficiency of the transmit/receive system as well as the beam containment values are addressed. These parameters are chosen to assess viability and feasibility of the energy augmentation method to establish safety for humans on-board from exposure to the transmitted energy. NASA will test the concept of operations in a laboratory experiment with parameters selected and presented in this paper.**

Keywords—eVTOL vehicles, microwave power beaming, AAM airspace operations

I. Introduction

There is increasing evidence that small and large electric air vehicles could be flying in lower altitude airspace (400-4000 ft.) within the next 10 years. A major research effort involving both the government and industry is in progress for the Urban Air Mobility (UAM) and the Advanced Air Mobility (AAM) concept implementation. AAM aircraft could be used to transport cargo and passengers in intra-city or inter-city operations, help with firefighting, and provide search and rescue operations. It also has the potential to connect underserved and rural communities [1]. A large number of these vehicles are expected to be electric vertical/short take-off and landing (eVTOL/eSTOL) systems, with a limited battery capacity, range/payload, and speed. When these vehicles arrive at their destination, they may need to hover or loiter for an extended period if, for example, there's a disabled vehicle on the vertiport final approach and take-off (FATO) area. On the other hand, the vehicles may face strong headwinds enroute or during arrival phases or incur mechanical/electrical issues during its journey that would require additional power or time. Electric battery characteristics indicate that when a high current is drawn from a low-charge-state battery, the depletion of battery charge is faster than when the same high charge is drawn from a high-charge-state battery [2]. Therefore, when these electric vehicles approach their landing pads at vertiports, and especially during severe weather conditions or other emergency situations, the approach process could become risky due to a depleted state of the battery. Several methods providing power to the vehicle have been presented and are being worked on. Eight concepts are presented in [3] and preliminary flying battery recharge experiments are demonstrated in [4] and [5].

This paper proposes a Concept of Operations (ConOps) for the power beaming of microwaves to electric air vehicles, during the arrival/descent phase of flight. This process could be utilized during the cruise and take-off phases as well but is beyond the scope of this paper. The aspects of airspace operations and microwave power beaming are covered here to augment energy of those vehicles. The concept envisions an arriving vehicle hovering at a predefined height. One or more transmitter(s) will direct microwave energy towards the rectifying antenna (or rectenna) on the vehicle at incremental power levels required for AAM energy augmentation. The initial parameters desired for such an energy augmentation process were estimated and the method of selection is described. The objective of this research is to establish parameters to conduct a safety study in an experiment, which identifies the exposure values for humans on-board from the transmitted energy.

The next section provides the concept of operations considering the impact on the airspace operations and how the power beaming would be accomplished. Section III provides the process of selecting the vehicle model (among the various

AAM vehicle types being considered), the characteristics of the transmitter antenna and the rectenna. Section IV, then, provides the current set of parameters under consideration. A discussion on the process of energy augmentation for AAM vehicles is presented. This process is being worked on with Defense Advanced Research Projects Agency (DARPA) and input from industry is being sought for desirability, viability, and feasibility of the proposed concept of operations. A future report will present the results of the experiment setup, testing of this energy augmentation method, and the exposure values from the power beaming.

II. Concept of Operations

The concept considered mission sizing, flight conditions, and aircraft evaluation in alignment with previously completed NASA-sponsored activities to incorporate power-beam-based energy for the vehicle. The concept envisions an AAM vehicle departing from the origin vertiport, flying at a cruise altitude, and descending to the destination vertiport, and the process of energy augmentation in instances when its desired, or in the future, a regular event. First, the airspace operations aspect is presented and then, the power beaming part is described. The concept of operations and the parameter selection is carefully defined to address the safety considerations of this method of energy augmentation.

A. *Airspace Operations Concept*

The airspace operations aspect addresses the handling by the Federal Aviation Administration (FAA) or the Provider of Services for UAM (PSU). The FAA would be concerned with the airspace constraints, while the PSUs would handle the instances for energy augmentation. Consider that an AAM vehicle is enroute to its destination vertiport. Along the way, it encounters strong winds or there is a disabled vehicle/unexpected debris at the destination vertiport final approach and take off (FATO) area. During both these events, the vehicle may need to hover or loiter, if there's not an alternate (diversion) vertiport available in the vicinity. The current concept addresses a vehicle being charged while it is hovering and not while it's moving (climbing, cruising, or descending), due to the complexity of a rotating transmitter system. Figure 1 illustrates schematically such a setup with a vehicle being charged by power beaming from a vertiport.

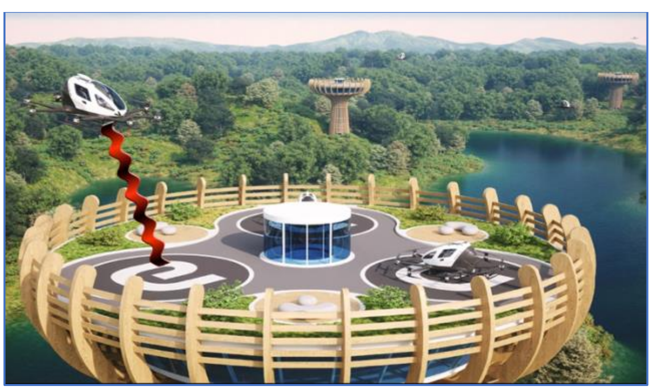

Fig. 1. Concept of power beaming for AAM vehicles.

Based on the proposed idea of microwave radio frequency power beaming, an airspace constraint will need to be set up. In conventional air traffic, a Temporary Flight Restriction (TFR), an Air Traffic Control Assigned Airspace (ATCAA), or a Special Use Airspace (SUA, if permanent) is set up for such events. One of the objectives of this study is to estimate the parameters of the blocked airspace that are required for such an airspace constraint to be established [6]. The other important parameter to assess is the duration for which such a constraint is required. This duration will also inform how long the humans on-board are exposed to the high energy beam.

This leads to another aspect of the use of energy augmentation for departure and cruise purposes as well, which is out of scope of this paper. However, the airspace constraint would need to be set up along the arrival or departure fixes or along the cruise phase of flight. Depending on the use case, the amount of airspace blocked, and the duration will need to be estimated. If the energy augmentation is for emergency situations, a TFR/ATCAA may be convenient and more efficient. If it becomes routine, due to other benefits like reduced turnaround time at the destination vertiport or extending range of the AAM vehicles, a permanent constraint in the form of a new type of SUA may be required.

B. *Power Beaming Concept*

The power beaming aspect deals with the actual process of microwave power beaming to recharge an AAM vehicle. Considering that without shielding, the microwave energy required for charging these vehicles is hazardous to exposed humans and other structures, it needs to address the control and containment of the power beam. This will be achieved through the utilization of digital or adaptive beam forming with a phased array antenna to enhance the beam output control authority and transmission distance.

Assuming the AAM vehicle is hovering (i.e., essentially stationary), a two-way communication reliability and ranging system needs to be setup between the vehicle and the charging infrastructure. This could be located at the vertiport or at another location (e.g., a tower enroute or a building/mobile structure in the vicinity). The two-way communication would assist in determining the transmission distance, duration, and power of the transmitter, in addition to providing station-keeping parameters to the vehicle.

Depending on the state of current charge in the vehicle, the amount of power required needs to be assessed. Based on the charge level and the type of vehicle, the transmitter would be configured and optimized to provide the output directed towards the vehicle. This is demonstrated in Fig. 2 (left) with a transmitter on top of a tower. If there was an obstacle of some sort in the path of the transmitter beam, the facility of multiple transmitters could be utilized, as shown in Fig. 2 (right), where three transmitters are illustrated. The alternative is to use a single transmitter with higher power for a longer duration. The time taken to augment energy of the AAM vehicle would inform the duration of the airspace constraint. Ideally, operations would be completed autonomously to optimize energy delivery from the system of ground transmitters to the airborne receiver(s) to reduce or eliminate operator input for energy augmentation services during descent and landing operations.

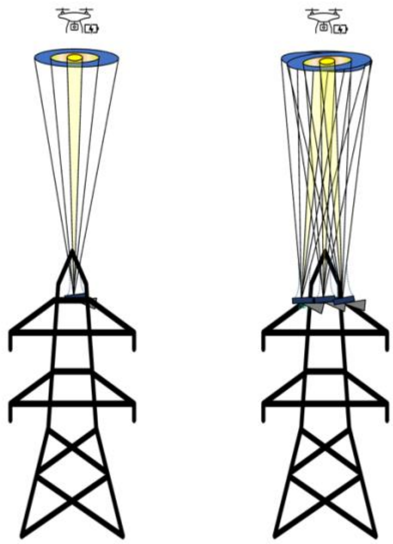

Fig. 2. Single or multiple transmitter(s) atop a tower for charging.

The power management and distribution system on the vehicle and the transmitter would dictate how much power can be transmitted to the vehicle; while the characteristics of the rectenna and thermal constraints will determine how much energy can be received.

The orientation of the vehicle has a significant impact on the reception of the transmitted power. The effective area of the beam collection will be reduced as the rectenna is pointed away from the transmitter, and hence, the power density per unit area is correspondingly reduced. Also, since the transmitted beam has a minimum angular spread due to diffraction, the distance of the hovering vehicle from the transmitter, in addition to the terrain reflectivity, impacts the amount of microwave charge available to it.

Based on the concept of operations description for airspace operations and power beaming, the parameters are explored. The method used for selection of the vehicle class desired for available charging is defined first. Then, the transmitter parameters for that model are presented. Last, the receiver parameters are described. As mentioned before, all these parameters are selected with human safety considerations in mind.

III. Parameter Selection For Vehicle Model

In the AAM literature, several models are considered and close to 800 vehicle designs in varying stages of design, development, and certification are presented in [7]. Reference [8] presents three classes of vehicles with differing performance characteristics. These are rotorcraft, lift+cruise, and vectored thrust models. Rotorcraft (e.g., Quadrotors or Side-by-Side) are vehicles which use the rotors for lift. Typically, vehicle tilting (similar to a helicopter) is used for forward motion. Lift+Cruise vehicles use completely independent thrusters for lift and cruise. Vectored thrust vehicles use any of the thrusters for lift and cruise.

One of the requirements for the vehicle is that the rectenna should introduce no additional drag during the flight. The bottom surface of all three models is the largest surface area that is available, for accommodating a no-drag rectenna. Therefore, the rectifying antenna would be integrated into the bottom structure of the vehicle either as a structural panel replacement or conformally coated on the surface of the vehicle. Table 1 shows parameters of the three vehicles considered from the NASA models [8]. The Side-by-Side (SbS) vehicle under consideration has a rectangular surface area of over 11.3 m^2. The L+C has 10.3 m^2 and the quadrotor has 9.5 m^2. These areas are close in value and the rectenna area is further described in Section V.C.

The lift+cruise vehicle with six passengers on board has a Design Gross Weight (DGW) of 8210 lbs. The side-by-side and the quadrotor with six passengers have DGW of 4897 lbs. and 6480 lbs, respectively. These numbers were obtained from [8] as well. Since the lift+cruise has the largest weight and will require the most beamed power. Therefore, Figure 3 (top) shows a perspective view of a lift+cruise model under consideration for power requirements. The bottom of Figure 3 shows a plan (top) view display of that lift+cruise vehicle model considered for charging. The rectenna area is further described in Section V.C.

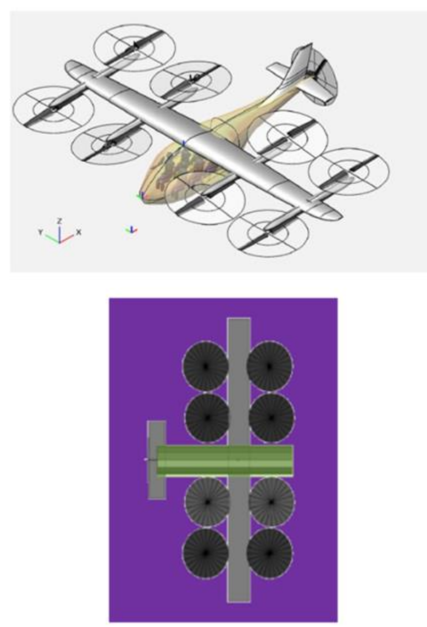

Fig. 3. Lift+Cruise vehicle consideration for charging mechanism.

The corresponding power requirements during hover and cruise phases are also provided in the table. As can be seen, hover takes more power than cruise. These play an important role as the vehicle is assumed to be in hover mode (due to a static and non-rotating transmitter) while its energy is being augmented.

TABLE I. VEHICLE SELECTION PARAMETERS.

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

IV. TRANSMITTER PARAMETER CONSIDERATIONS

Technologies and innovative solutions for efficient, all-, weather kilowatt-class microwave power beaming operations up to a kilometer in distance were evaluated for the concept of operations. High-power and high-efficiency ground transmitters optimized for cost, size, and resilience capable of scalable architectures configurations (ground, mobile unit, and tower) are envisioned for the operational system. The method used to select the microwave transmission frequency is described next.

The radio frequency (RF) chosen for transmission is the result of a trade-off between the narrower beam width produced by beams of higher frequency (to be explained in Section IV.C), against the higher device efficiency and greater independence from weather effects experienced at lower frequencies. Beam collection efficiency, $\eta_{collection}$, is the ratio of the power received P_r over the power transmitted P_t. As shown in (1) and (2) below, the beam collection efficiency represents the fraction of the beam intercepted by the receiver at a given distance, D, for an optimized beam, and is a function of the wavelength, λ. The parameter τ is a ratio proportional to the diameters of the transmitter and the receiver, and inversely proportional to the wavelength and the distance D from the transmitter [9]:

$$\eta_{collection} = \frac{P_r}{P_t} = 1 - e^{-\tau^2} \quad (1)$$

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

where A_t and A_r are the areas of the transmitter and receiver. Note that $\lambda = c/f$ is the speed of light divided by the frequency. This equation is strictly applicable only for a circular transmitter and receiver, but is a reasonable approximation as long as the transmitter and receiver shapes are not too irregular.

A. Transmitter Antenna Size

In (1), the parameter τ is proportional to the square root of the transmitter antenna area, A_t, and hence, larger transmitter antenna area will result in a greater value of τ, and correspondingly greater power beam collection efficiency. Larger transmitting antennas, on the other hand, also increase price and complexity. For the baseline case, the area of the transmitting antenna is set to 9 m^2, a compromise between the higher efficiency of a large antenna against the higher cost. For the lift+cruise vehicle, the resulting elliptical surface area of the columnated beam is calculated to be 10.3 m^2 and the transmitter size of 9 m^2 is the maximum for consideration. Larger transmitter sizes could be considered for the testing system.

B. Transmitter Frequency

Lower frequencies (such as 1.5 GHz) result in a low amount of the beam getting collected due to the wide beam divergence. However, there are also shortcomings at higher frequencies. For frequencies above the X-band (8-12 GHz), atmospheric losses (primarily due to water droplets, and, at higher frequency, even water vapor) increase rapidly. These losses would limit the applicability of power beaming to clear weather. Since the baseline is for all-weather capability, the frequency choice is restricted to either the X-band or C-band. The C-band, encompassing the frequencies from 4-8 GHz, includes a band allocated to Industrial, Scientific, and Medical (ISM) uses at 5.8 GHz. Due to the well-developed technology, this 5.8 GHz ISM band was selected for initial investigation, but a future investigation at a higher frequency may also be worth pursuing.

A 9 m^2 transmitter and a few frequencies were compared based on the generic flight profile [8]. These are shown in Table II. Figure 4 shows the curves for the power beam collection at different frequencies. It's observed that $\eta_{collection}$ is higher at larger frequencies, and lower farther out. For the same transmitter area, it is better for a larger receiver area.

TABLE II. SELECTION OF POWER BEAMING COLLECTION EFFICIENCIES.

	1.5 GHz					
Flight Profile	At 500 ft	At 1000 ft	At 1500 ft	At 2000 ft	At 2500 ft	At 5000 ft
Quad	7%	2%	1%	0%	0%	0%
SbS	8%	2%	1%	1%	0%	0%
L+C	8%	2%	1%	0%	0%	0%
	5.8 GHz					
Flight Profile	At 500 ft	At 1000 ft	At 1500 ft	At 2000 ft	At 2500 ft	At 5000 ft
Quad	66%	24%	11%	7%	4%	1%
SbS	72%	28%	13%	8%	5%	1%
L+C	69%	25%	12%	7%	5%	1%

	10 GHz					
Flight Profile	At 500 ft	At 1000 ft	At 1500 ft	At 2000 ft	At 2500 ft	At 5000 ft
Quad	96%	55%	30%	18%	12%	3%
SbS	98%	62%	35%	21%	14%	4%
L+C	97%	58%	32%	20%	13%	3%
	35 GHz					
Flight Profile	At 500 ft	At 1000 ft	At 1500 ft	At 2000 ft	At 2500 ft	At 5000 ft
Quad	100%	100%	99%	91%	79%	33%
SbS	100%	100%	99%	95%	85%	37%
L+C	100%	100%	99%	93%	82%	35%

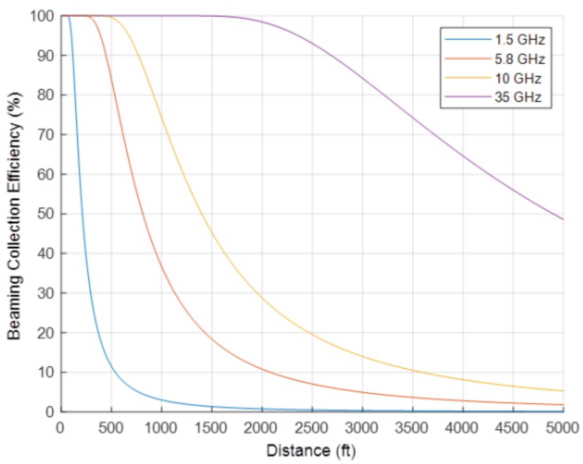

Fig. 4. Comparison of collection efficiencies at different frequencies.

C. Transmitter Beam Width

The microwave beam transmitted to the aircraft will have a beam width that is defined by its diffraction pattern [10]. This is determined by the wavelength λ of the microwaves, and the size of the transmitting dish or phased array. For calculations, the assumption is made that the transmitting antenna is a uniformly illuminated disk*, allowing the use of Fraunhofer diffraction equation. The beam thus consists of a central "hot spot" of high intensity ("Airy disk"), surrounded by diffraction side-lobes (or "wings") of progressively lesser intensity as a function of the angle, as seen in Figure 5.

The central hot-spot is defined by distance to the first null in the diffraction pattern. The half-angle of the central hot spot, which contains 87% of the beam power, is:

$$\theta_{central} = 0.61(\lambda / r_t) \quad (3)$$

For the assumed frequency of 5.8 GHz, λ is 5.17 cm, and the half-angle of the central beam (for a 9 m^2 transmitter) is 1.1°. Figure 5 shows the intensity as a function of angle.

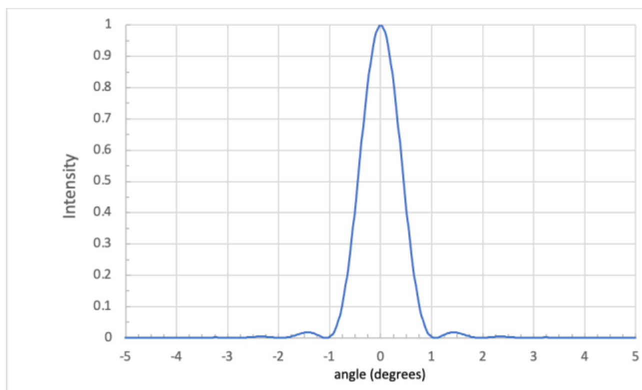

Fig. 5. Beam intensity as a function of angle.

As is shown in figure 5, the fringes or "wings" of the beam are much lower in intensity than the central beam but are non-zero. While the wings do not contribute significantly to the power, the intensity can be high enough to require a safety keep-out zone, in which unshielded humans need to be excluded. Figure 6 shows the central hot spot, the side lobes, and other fringe regions in a schematic.

* a non-uniform illumination can improve the profile of the beam slightly, but to a first level approximation, the amount that can be gained is small.

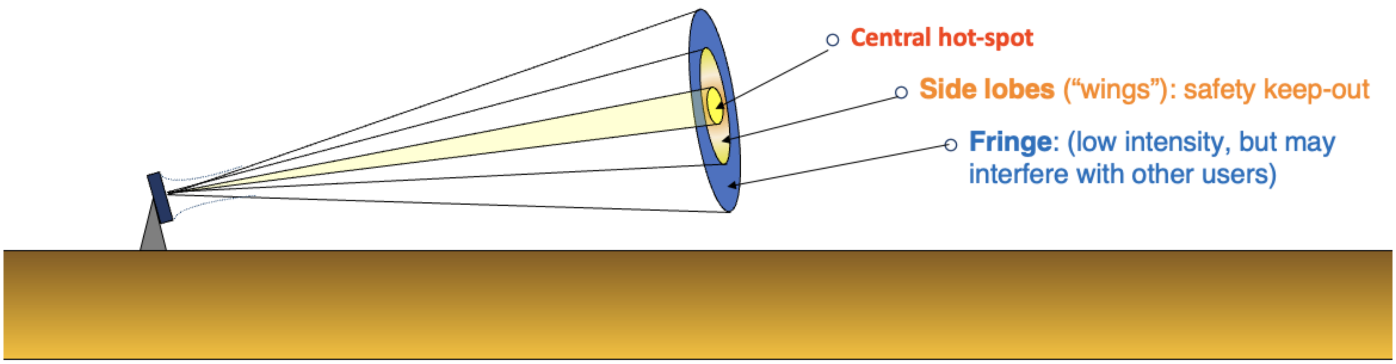

Fig. 6. Schematic showing central hot-spot and keep-out zone of the beam.

V. Rectenna Parameter Considerations

Based on the selection for the transmitter frequencies, the receiver parameters are addressed next. The rectenna should have high-power and high-efficiency radio frequency (RF) to electrical (DC) conversion receivers compatible with small airborne vehicles.

A. RF to DC Efficiency

The RF to DC conversion efficiency is a function of the frequency and the technology selected. For the 5.8 GHz beam, an efficiency of 70-85% in the rectenna is expected. For clarity, this metric is not stating that 70-85% of the power transmitted will be the power received due to atmospheric losses. In the most rudimentary view, the power transmitted must be converted to an RF signal, transmitted, received, and converted back to DC power. Given the reasonable losses that will occur at each step, the primary focus of this parameter is to provide a benchmark for the conversion from the received signal back to DC.

B. Power Density

The weight of the Power Management and Distribution (PMAD) hardware is important as it could impact the overall vehicle weight. The PMAD value selected is 6 kW/kg. Optimistic estimates have PMAD components at up to 9 kW/kg [11], however, a lower value is selected to account for some diminished performance in practical application versus the simulated environment.

C. Rectenna Size

The receiver antenna area, denoted A_r in (2), determines τ. Thus, a larger receiver antenna area will result in a greater value of tau, and consequently greater power beam collection efficiency. To create a no-drag solution, the rectenna size is constrained by the size of the AAM platform. The rectenna should be sized for integration onto electric aerial vehicles so that it would be an in-kind structural panel replacement or equivalent to the size and mass of a primary flight battery.

The vehicle designs chosen, provide an area of roughly 9-12 m^2 under the fuselage and is the catalyst for the sizing decision. The size of the rectenna is currently anticipated to be about 11 m^2, as mentioned earlier.

VI. Combined Transmit/Receive Parameters

The combined efficiency of microwave energy transmission and reception as well as the transmit beam containment are applicable for the entire energy augmentation process. They are described next.

A. Combined Efficiency

The combined efficiency, determined by multiplying the power beaming collection efficiency and the RF-to-DC conversion efficiency of the rectenna, is described here. This efficiency provides a benchmark for standardization. To justify the extra safety precautions and advanced hardware configuration, currently, a minimum combined efficiency of 40% is set as a requirement. Table III outlines the combined efficiencies considering angles of incidence of the rectenna to the transmitter beam of 90°, 45°, and 15°, with the test parameters of transmitter area of 9 m^2, lift+cruise as the vehicle type, and a frequency of 5.8 GHz are used for the table calculations. The additional losses that occur as a function of converting DC power to an RF signal to transmit to the rectenna is about 5%. The additional losses are ignored for this combined efficiency currently, but in the future may become important.

The best-case RF to DC conversion efficiency (described in V.A above) of 0.85 is used in (4) to compute the values of combined efficiencies at different incidence angles. These values are presented in Table III.

$$\eta_{combined} = \eta_{collection} * 0.85 * \sin(\,Angle\,). \quad (4)$$

TABLE III. COMBINED EFFICIENCIES AT DIFFERENT ANGLES.

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%
15° Angle	22%	15%	6%	3%	2%	1%	0%

B. Beam Containment

Safety standards for exposure to energy from the microwave beam or to energy scattered from the microwave beam are taken from the International Commission on Non-Ionizing Radiation Protection Guidelines for limiting exposure to electromagnetic fields [12]. This will be used to establish "keep-out" zones to prevent humans from being exposed to health risks. For people outside the aircraft, we define a keep-out zone as the regions with power levels above 20 W/m^2, adopted from the safety limits for 2-6 GHz microwave energy for exposure times of up to 6 minutes (Table 6 of [12]). For the pilot and passengers inside the aircraft, we adopt a slightly more stringent limit of 10 W/m^2, from the safety limits for exposure times of up to 30 minutes (Table 5 of [12]). Industry [13] has previously accepted these limits in past experiments and successfully demonstrated their compliance.

VII. RESULTANT PARAMETERS

With the parameter selection described above, the parameters have been chosen that define the energy augmentation method of microwave power beaming under consideration in this research. Table IV lists the name, description, and range of the parameters. For the experiment to be conducted, some bounds around the chosen values are prescribed in the table to account for cost and feasibility of the proposed concept and available hardware.

Since the power requirements for each of the three models, i.e., the quadrotor, the side-by-side, and the lift+cruise, are very different, no specific model is being considered for immediate implementation, but their rectenna areas are chosen. The power requirements indicate that side-by-side model power and area may be more suitable, but the calculations and future direction will not eliminate the other two from being considered.

Based on the beam width presented in Fig. 5, the subtended half-angle calculations of 1.1º indicate that if the vehicle (and hence, the rectenna) is located 1000 ft from the transmitter, the width of the full beam, w, at that distance is defined as

$$w = 2 * D * \tan(\theta_{central}). \tag{5}$$

Based on D = 1000 ft and half-angle $\theta_{central}$ of 1.1 degrees, w is 38 ft. Thus, a conical (or rectangular, for simplicity) airspace constraint of that size needs to be established. Based on the interference that this beam could cause to the rest of the environment (i.e., structures, frequency interference, etc.), a prismatic airspace constraint from hover height to the ground should be implemented. Based on the calculations, this is the impact on the airspace operations. The time needed to keep this TFR or ATCAA depends on the amount of time desired to augment the energy of the AAM vehicle. The PSU would provide that number to the FAA.

TABLE IV. PARAMETER CONSIDERATION LIST.

Parameter	**Description**
Vehicle model	Side-by-Side (SbS)
A_{TX}	Maximum area of the transmitter aperture = 9 m^2
f	Frequency of operation = 5.8 and 10 GHz
D_{TRX}	Distance between the transmit and receive apertures = 100 to 1500 ft
A_{RX}	Maximum area of the receiver aperture = 9 to 12 m^2
$P_{TX\text{-}out}$	Transmitter power output at frequency of operation = 2.5 to 250 kW
$P_{RX\text{-}in}$	The power incident on the receive aperture = 2 to 210 kW

For power beaming to the vehicle types under consideration, the transmit power of 2.5 kW is low. For 2.5 kW, the required duration of charging would be long, and infeasible. Thus, higher power transmitters, going up to 250 kW, will be considered, as shown in the table. Also, in the future, with transmitters that can rotate, the hover requirement should be removed. That would allow the vehicle to be charged while moving, and consuming lower power than hovering.

VIII. CONCLUDING REMARKS

A Concept of Operations for the charging of electric Vertical Take-Off and Landing (eVTOL) vehicles has been proposed in this paper. The concept addressed the airspace operations and the power beaming aspects of this mechanism.

The parameter selection methods for the electric air vehicle, the transmitter, and the rectifying antenna were described. Based on those, a preliminary selection of parameters was presented. A table of parameter values, that represent an experiment to conduct feasibility of such a process was presented in the previous section.

These parameters will be used in work with the partners at DARPA and the industry to devise an experiment for microwave power beaming for energy augmentation of the AAM vehicles. These parameters also serve as a starting point for NASA to test and demonstrate this concept of operations in a laboratory environment and then in a remote, sparsely populated area. The main objective is to assess the energy exposure levels for the humans on-board the AAM vehicle and to assess their safety, due to this indirect method of charging.

The required duration of charging required will have a significant impact on the safety, viability, and feasibility of this method of energy augmentation. Based on preliminary experiments conducted by industry, it appears that a set of parameters will be identified from the initial-value ranges for the system considered here, to make this method of microwave beaming possible. It is apparent that the 2.5 kW system would not suffice to augment the energy of the models under consideration and would require higher power systems. Subsequently, the thermal environments and rectenna materials will need further investigation and will be reported in a future article.

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