CREATeV: An Evaluation of Solar Charging Optimization for Ultra-Long Endurance Flight

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Abstract

Over the past four years the Clean Renewable Energy Aerial Test Vehicle (CREATeV) solar-powered UAV has completed a total of 23 hours of flight testing. This testing has identified a need for a theoretical model to predict the solar power intake of the aircraft. Using this data and the power required, different loiter circuits can be evaluated to select the most beneficial path. This model analyzes each flightpath by evaluating when the aircraft's batteries are charging or discharging. The model also takes into consideration the effects of wind, heading, date, and time of day. Experimental data collected during a 10 hour flight conducted in November 2020 is used to develop an understanding of the vehicle's level flight power required. This model will be used to maximize the net power gained from the sun during daylight hours, and improve the chances of completing future multi-day flight tests with the CREATeV vehicle.

Nomenclature

$C_{L,tf}$ = Lift Coefficient of Turning Flight
$C_{L,lf}$ = Lift Coefficient of Level Flight
ϕ = Roll Angle
P_{req} = Power Required
ρ = Air Density
V = Velocity
S = Wing Area
$C_{D,tf}$ = Drag Coefficient of Turning Flight

P_{solar} = Solar Power
A_{Solar} = Solar Array Area
$\eta_{Solar\ Cells}$ = Solar Cell Efficiency
η_{Solar} = Solar Efficiency
P_{motor} = Motor Power
P_{excess} = Excess Power
$P_{maneuver}$ = Maneuver Power
$P_{thermals}$ = Thermal Power

1. Introduction to the CREATeV Project

The goal of the CREATeV project is to break the world record for the longest unmanned flight. The current record of 25 days, 23h and 57min was set by Airbus Zephyr in 2018 [1]. The CREATeV vehicle, shown in flight in Fig. 1 below, is a 6.28m fixed wing, ultra-long endurance unmanned aerial vehicle that features a wing-mounted solar array [2]. The solar array provides excess power during daylight hours to charge onboard batteries that are used to sustain flight during the night. Over the past four years, two flight test vehicles have been built and four flight tests, totalling 23 hours of flight time, have been completed, with more planned for the summer of 2021.

Figure 1. The CREATeV flight test vehicle in flight on November 11, 2020.

Early flight testing of the CREATeV vehicle has identified several areas that can be addressed to increase the probability of breaking the world endurance record; these include: flight path optimization, and a better understanding of the aircraft's power consumption and solar power available. This is being accomplished with the development of a model that addresses the aircraft's required power for various maneuvers and the energy gained from the solar arrays. Due to the ever-changing orientation of both the vehicle as well as the sun throughout the day, a model was generated to calculate the net power consumed during a variety of loiter circuits that allows for varying wind magnitude and direction, and sun locations. Each of these factors are vital to determining the fastest rate at which energy can be gained during the day to charge the batteries in preparation for the night.

2. Development of a Theoretical Energy Model

To help explore the choices and variables that were explored during the development of the theoretical and experimental models, Fig. 2 outlines the inputs and relevant outputs of the developed energy model. This flow diagram shows the intermediate stages of the analysis outlined in the herein paper, and the relationship between the factors described and the desired loiter energy term.

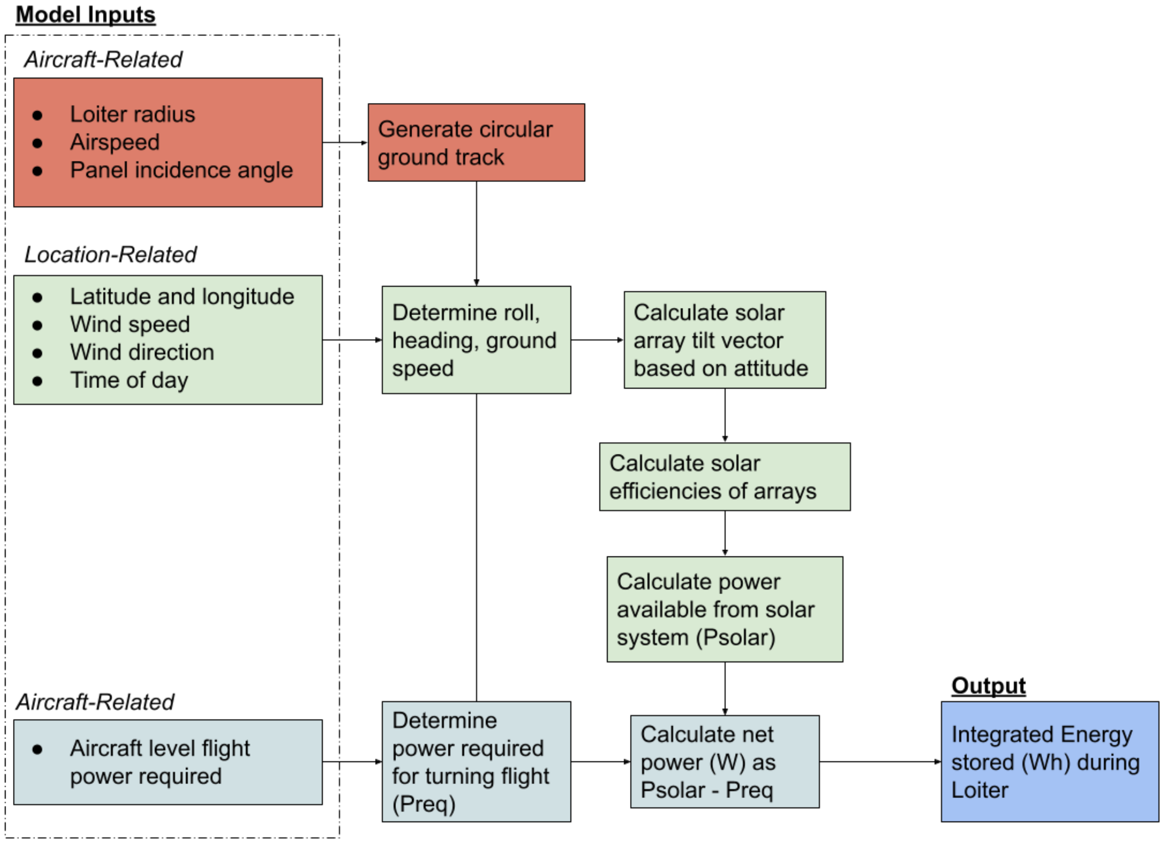


Figure 2: Flowchart describing the modules in the developed solar energy model.

The model begins by representing a loiter circuit with discrete segments along a circular ground track at a desired airspeed and radius. Knowing the wind speed and direction allows for the calculation of the unknown airspeed vector direction and the unknown ground speed magnitude. With the calculated aircraft orientation and known position and time of day, the solar array normal vector can be found at each of the discrete segments in the loiter.

While developing a solar charging model, one of the most important factors to consider is the cosine relationship that will determine what percent of the available power is converted into electrical power by the solar cells. This cosine relationship is represented using the sun vector that comes into contact with the upper surface of the aircraft, and is used to determine the power available from the solar array at each of the points in the loiter. This calculated solar power available is used to charge the onboard batteries, as well as provide the power required to maintain flight while turning.

To be able to better analyze the survivability of the aircraft, a day-to-day model is being generated that tracks and optimizes the location and orientation of the aircraft over a twenty-four-hour period. During mornings, following sunrise, the sun will crest the horizon and therefore will be below the aircraft resulting in only small charging rates. Based on this non-ideal sun vector, the model that is explored in the following evaluation has to consider the power required to bank towards the sun and what net power gains can be achieved within the available flight envelope.

2.1 Theoretical Model, Power Consumption

This model will allow for an estimation of the power required to complete specific flight paths, and will be crucial for the net power discussion that will follow in the next section.

Assuming a constant airspeed, the coefficient of lift in level flight can be related to an equivalent turning flight coefficient [3] using:

$$C_{L,tf} = \frac{C_{L,lf}}{\cos(\phi)} \quad \text{Eq. 1}$$

With the turning flight lift coefficients, turning flight drag can then be interpolated from level flight drag predictions. These drag predictions are currently found using a vortex lattice based potential flow code with additional profile drag added using a strip theory approach, and the drag of the fuselage accounted for as the skin friction for an unrolled cylinder. This provides an acceptable means of estimating the total drag, which will be improved upon with a flight test approach, as described in section 4.

Since the methodology takes into account the different factors concerning flight, such as, wind speed, sun angle, and flight direction, the lift coefficients calculated are representative of actual flight characteristics. The acquisition of turning flight lift and drag coefficients will allow us to calculate the power required for turning flight based on:

$$P_{req} = \frac{1}{2}\,\rho V^3 S C_D, tf \quad \text{Eq. 2}$$

where, ρ is the density of air, V is the airspeed of the aircraft during flight, S is the wing area of the aircraft, and $C_{D,tf}$ is the turning flight drag coefficient calculated. Although initially set up for a specific scenario, this model can be adjusted to accommodate various flight circumstances, thus allowing for the estimation of necessary power, for any given climate.

The development of an estimated understanding of the power consumed by the CREATeV vehicle allows for a net power model to be generated, this model will allow for an estimation of the net power change experienced by the aircraft, including the power gains from the solar charging systems. To apply this model a separate exploration of the effects of the solar positioning and aircraft attitude was completed and is outlined in the following section.

2.2 Theoretical Model, Net Power Change

The success of the project requires a good model that monitors solar efficiency. Utilizing current flight constraints (i.e airspeed, turning direction, and loiter radius), a representation of the solar efficiency can be created. An important constraint for this model is the loiter radius, as the results that follow rely heavily on this initial entry. In order to create a more suitable model, the loiter radius will be divided into 70 segments on the circular ground path. Once segments have been established for a given loiter radius, the roll angle at each point is then calculated accounting for the airspeed and wind vector magnitude and direction. This allows the mapping of the plane's positioning, and therefore the solar array, relative to the sun, and thus will allow us to calculate the expected solar efficiency, given geographic coordinates, time of day and year, and general flight constraints.

The calculated solar efficiency is found as cosine of the angle between the cell normals and the vector from the plane to the sun [4], The rated solar efficiency can thus be converted into power with the relationship shown below:

$$P_{solar} = (A_{solar})(\eta_{solar\ cells})(\eta_{solar})(avg\ solar\ irradiance) \qquad \text{Eq. 3}$$

Where A_{Solar} is the solar array area,η_{solar} is the solar efficiency calculated, the average solar irradiance is the solar irradiance available (in W/m^2) , and $\eta_{Solar\ Cell}$ is the solar cell efficiency.

2.3 Theoretical Model, Results

At this point, calculations regarding the plane's power consumption behavior during turning flight are made. Using the calculated solar power available, and the necessary power required for turning flight at a given roll angle, it can be determined whether the plane is charging or discharging during each segment. The figure below showcases the power consumption model at a loiter radius of 347 m, flying a clockwise loiter circuit, at a constant airspeed of 11 m/s, and a windspeed of 5 m/s at a 20 degree heading.

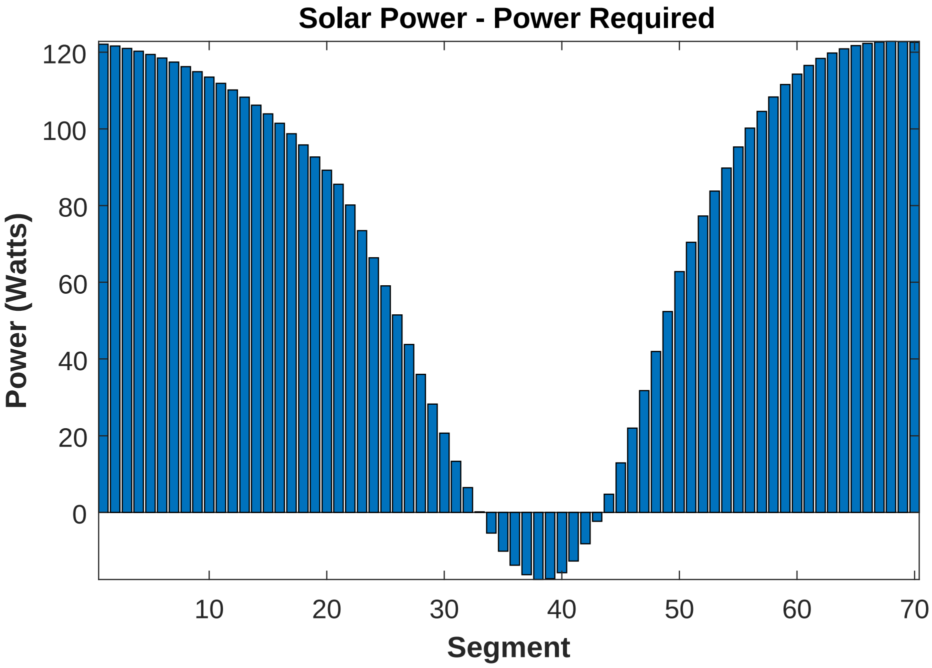
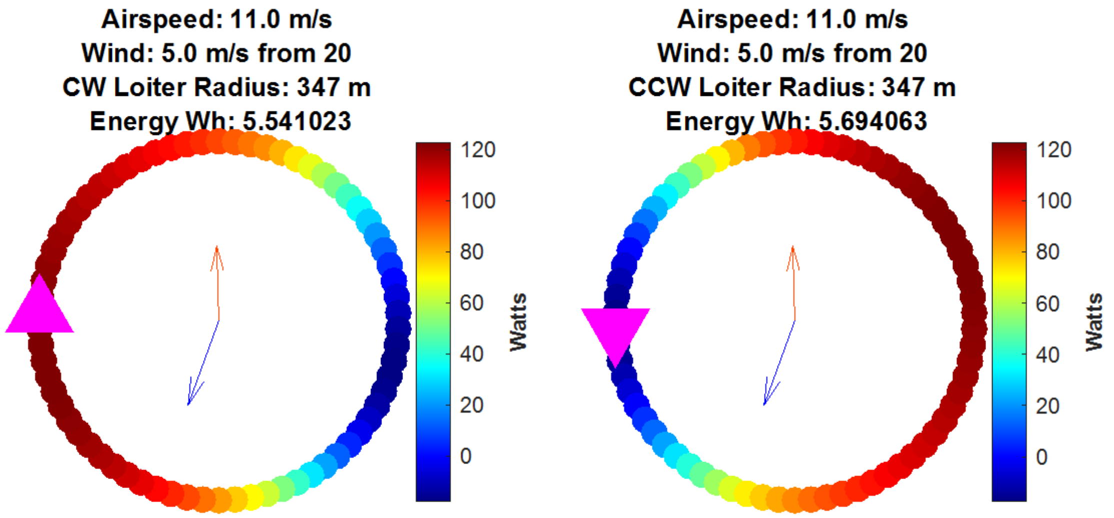


Figure 3: Power Absorbed/Consumed vs. Segments.

Figure 3 displays the power results in a simulated clockwise loiter. Each column represents one segment in the circuit and corresponds to a latitude, longitude, time of day and year, roll angle, pitch angle, and heading. The power values recorded are calculated at specific roll angles. Each column represents the net power available to the aircraft during that specific segment. Positive values indicate that there is more solar power available than the power required to sustain flight, negative values indicate the aircraft does not possess more solar power than power required to sustain flight, and will thus use power stored in batteries.



(a) (b)

Figure 4: Power Absorbed/Consumed in a Circular Flight Path while traveling (a) Clockwise and (b) Counter Clockwise.

Figure 4 graphically displays the results of a simulated clockwise loiter circuit. Each dot represents one segment in the circuit, and will have a corresponding latitude, longitude, time of day and year, roll angle, pitch angle and heading. The blue vector represents the wind vector of 5.0m/s from a 20deg direction, and the red vector represents the vector from the sun. In Fig. 4, the results are calculated when the sun is directly south of the aircraft. The magenta triangle is simply to represent the aircraft's direction in the loiter. The color of each dot represents the net power available to the aircraft during that specific segment. Positive values indicate that there is more solar power available than the power required to sustain flight, this means the aircraft batteries will be charging. Negative values indicate the batteries will be discharging. Integrating the power available over the time of each segment results in the total energy gained or lost from the batteries, measured in Wh, for one loiter circuit.

As observed in Fig. 4, the plane charges for the majority of the flight path, when flying against the wind, alongside instances where the sun is at a disadvantageous position relative to the plane, it discharges the batteries. For this example, the aircraft gained 5.54Wh of energy while flying this clockwise loiter. This model allows us to create an optimal flight path for the plane, by applying certain constraints in order to maximize power absorbed, while minimizing the power used to complete various maneuvers.

Based on the provided data and figures, a general model for the plane's flight path can be considered. It is important to note that in order to maximize charging, the plane must spend a greater amount of time flying whilst the solar array is facing the sun. This can be accomplished by flying slower, however, it can also be accomplished by adjusting the flight path. As seen in Figure 4, one half of the path provides a far more advantageous position for the aircraft to charge. This is primarily due to the fact that the orientation of the solar cells relative to the sun is at a more advantageous position, however, it is also due to headwinds allowing the aircraft to spend more time in this section. To take advantage of this, the aircraft's flight path should be altered to ensure it spends the majority of the flight time within that area.

3. Power Balance Discussion

The previously discussed model explores the theoretical net power changes given specific criterion. To support this model, experimental data collected during the 2020-2021 flight tests was evaluated. Data was collected for the entirety of the flights that lasted, at maximum, ten hours; the data represents the dynamic, kinematic, and electrical characteristics of the aircraft throughout the tests. During the chosen ten-hour flight, which took place primarily during daylight hours, a series of maneuvers were completed that would allow for specific conditions to be evaluated. The first of these conditions to be tested was a series of zero-throttle descents followed by constant throttle climbs which allows for the number of variables to be reduced.

To develop an understanding of what is being represented with the flight test data the following power balance equation was used.

$$P_{required} = P_{motor} - P_{excess} - P_{maneuver} - P_{thermals} \qquad \text{Eq. 4}$$

The equation shown above represents the balance of the power gained and the power expended by the aircraft. In this case the motor power (P_{motor}) represents the electrical power inputted into the motor multiplied by an efficiency factor. This factor represents a combination of the wire losses, propeller efficiencies, and motor efficiencies. It is important to note that this factor is dependent on the current, for the wire losses, and experiences a higher magnitude when the propeller changes RPM. This spike is due to the acceleration of the propeller and motor inertia, requiring a higher torque.

The excess power term is the combined change of the kinetic energy and the potential energy. To develop this value the aircraft's instantaneous velocity and altitudes were measured at a frequency of 25Hz during flight testing. This excess power term represents the power fluctuation of the aircraft due to climbing or accelerating throughout the flight.

The final two variables outlined in the power balance equation represent difficult to quantify values during flight and therefore are avoided in the data analysis. To do this, the data had to be filtered for a variety of conditions that would allow for only the required power to be solved for. The first filter applied involved removing any section with a bank angle larger than 3 degrees, this meant that the aircraft was in a non-turning state and the maneuvering power was minimized. A second filter removed all non-zero throttles. With this filter it can be assumed that there is no change in RPM, therefore no extra power was required to accelerate the propeller.

Figure 4 outlines the instantaneous altitude, velocity, and calculated power required terms throughout a 1200 second flight test. During this time a series of constant velocity climbs with zero-throttle descents were completed. The sections that are highlighted in red on the altitude graph represent locations that satisfy the filters outlined previously. In some locations, such as at 620 seconds, an increase in altitude is experienced while a negative required power is displayed. This negative required power term should not exist, and represents an unaccounted for power quantity. At this location there would have to be another source of power to generate upward motion, this could be caused by the presence of thermals.

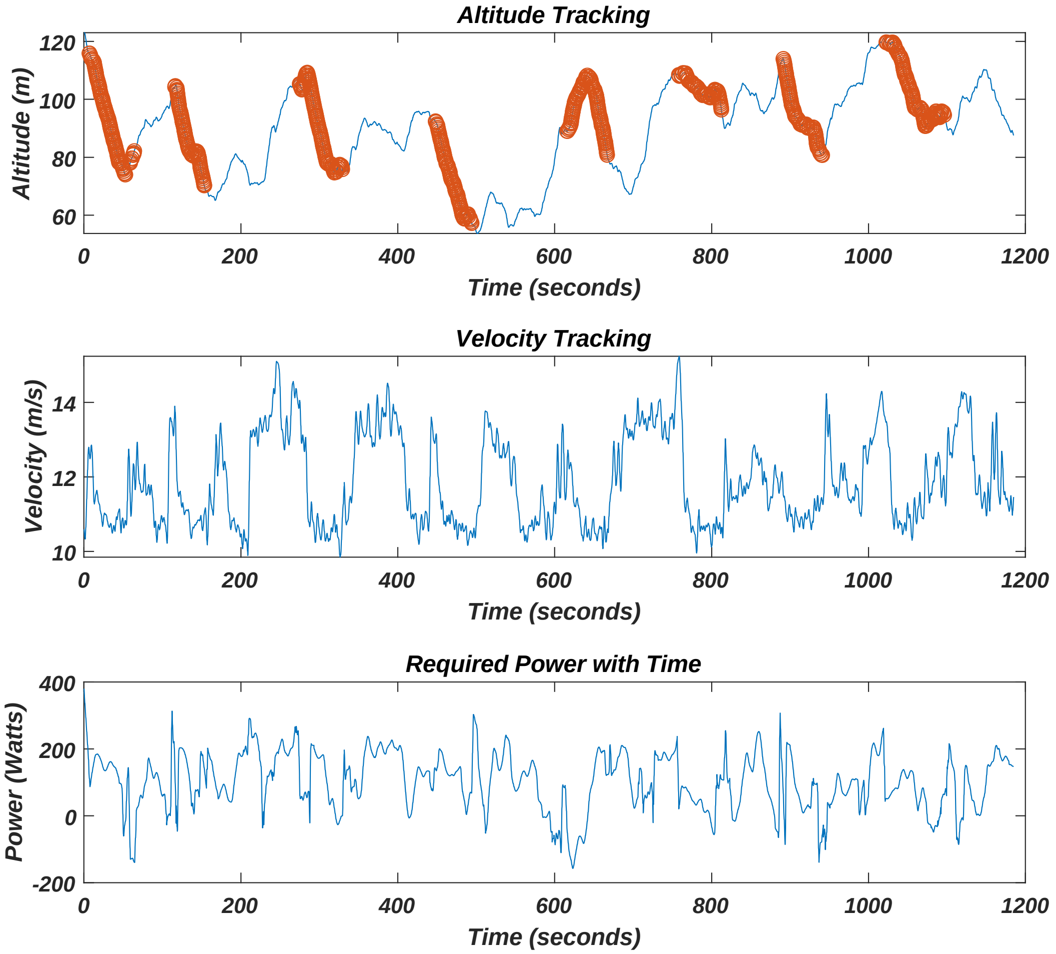


Figure 5: Altitude, velocity, and combined power required chart with respect to time in seconds.

The observation of thermalling locations within the data, shown in Fig. 5, poses a large problem for this evaluation, as there are locations of negative required power, which is not possible. On top of this issue, it is not possible to determine where, and to what magnitude, other locations are affected. Meaning, while the presence of an unaccountable power increase confirms the existence of an unaccounted for power term, such as thermals, it does not comprehensively outline which data is, and is not affected. For this reason, the current model is inconclusive with the current set of data. However, with this information a set of criteria was developed to ensure quantitative and conclusive data for the future flights.

Similar problems have been documented where thermals and wind gusts have caused unexpected spikes in the data and restrict the ability for the model to develop a comprehensive understanding of the flight characteristics. In Ref. 5, a variety of suggestions are made to reduce these extraneous variables causing variations in the data. These suggestions were considered and applied while developing the future flight test plans.

Using the information determined in this exploration of the power balancing equation a set of requirements was developed for future flight tests to create a valid comparison between the theoretical model proposed previously and the experimental model outlined in this section. Combined with the zero-throttle filter and the small roll angles, time constraints will be applied to future flight tests. This constraint will involve collecting data during the night or in the early mornings when the ground has not had time to heat up and generate thermals. This method would reduce the irregularities that were noticed in the previous data and would allow for a comparison between the theoretical model and the flight data.

4. Summary

To date, the CREATeV vehicle has flown four separate flight tests with over 22 logged hours of flying, in these tests an understanding of the aircraft's performance and capabilities were developed. To further develop the aircraft for ultra-long endurance flights, an understanding of the flight path optimization needs to be developed. To do this, a theoretical model was developed that outlines the estimated net power changes of the aircraft given a specified circular path. This model considers the time of year, the Sun location throughout the day, as well as the prevailing wind directions. The combination of all these factors allows for an estimation of the amount of power that can be gained, provided the time of day and wind vector is known. This will allow for on the spot adjustments to the flight path given specific criteria developed from the model.

After generating a theoretical model to outline the net power changes a comparison was completed with the collected flight test data. This comparison aimed to validate the power draw described in the theoretical model. Currently the flight tests that have been completed do not satisfy this specific model as the presence of unaccounted for power terms, such as thermals, have outputted a negative power required term. Based on this future flight tests will focus on reducing the extraneous power terms by tailoring the flight to satisfy the model's requirements. In the future the CREATeV vehicle will further develop as an ultra-long endurance vehicle and will aim for multi-week flights.

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