Solid State Aircraft

Phase I Project

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NIAC Headquarters
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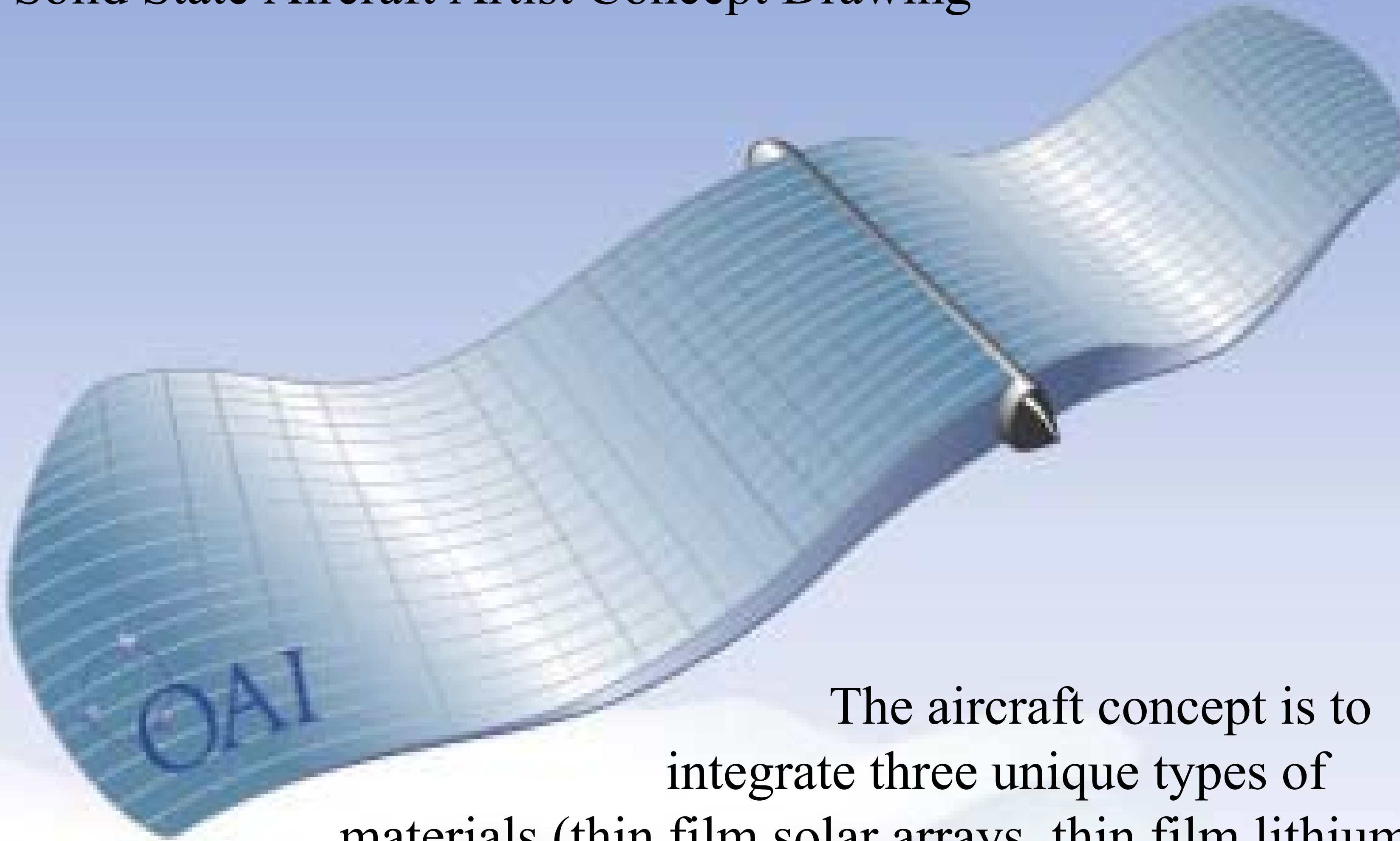
Solid State Aircraft Artist Concept Drawing



The aircraft concept is to integrate three unique types of materials (thin film solar arrays, thin film lithium batteries and an ionic polymer metal composite) to produce an aircraft that has no moving parts, can fly at high altitudes, is easily deployable and has applications on Earth, Venus and Mars

Aircraft Operation

The aircraft operates by collecting and converting sun light to electricity through a thin film photovoltaic array. This electricity is then stored in a battery.

At specified intervals the energy is discharge to the anode and cathode grids to set up an electric field about the IPMC (synthetic muscles)material This electric field causes the IPMC to move thereby causing a flapping motion of the wing.

This flapping motion produces lift and thrust for the aircraft.

The electric field generated by the grids is controllable, therefore the shape and motion of the wing is controllable on each flap.

Material

Anode Grid

Aircraft Construction & Control

- The unique structure combines airfoil, propulsion, energy production and storage and control.

- To control the motion of the wing a control grid will be used. This grid will enable various voltages to be sent to different sections of the wing, thereby causing varying degrees of motion along the wing surface. The amount of control on the wing will depend on the fineness of this control grid. A central processor will be used to control the potential of each of the sections.

- This control enables the wing to fla
provide differential lift (which is u
for steering), and alter the camber
of the wing to maximize lift
under a given operational conditio

Thin Film Photovoltaic Array

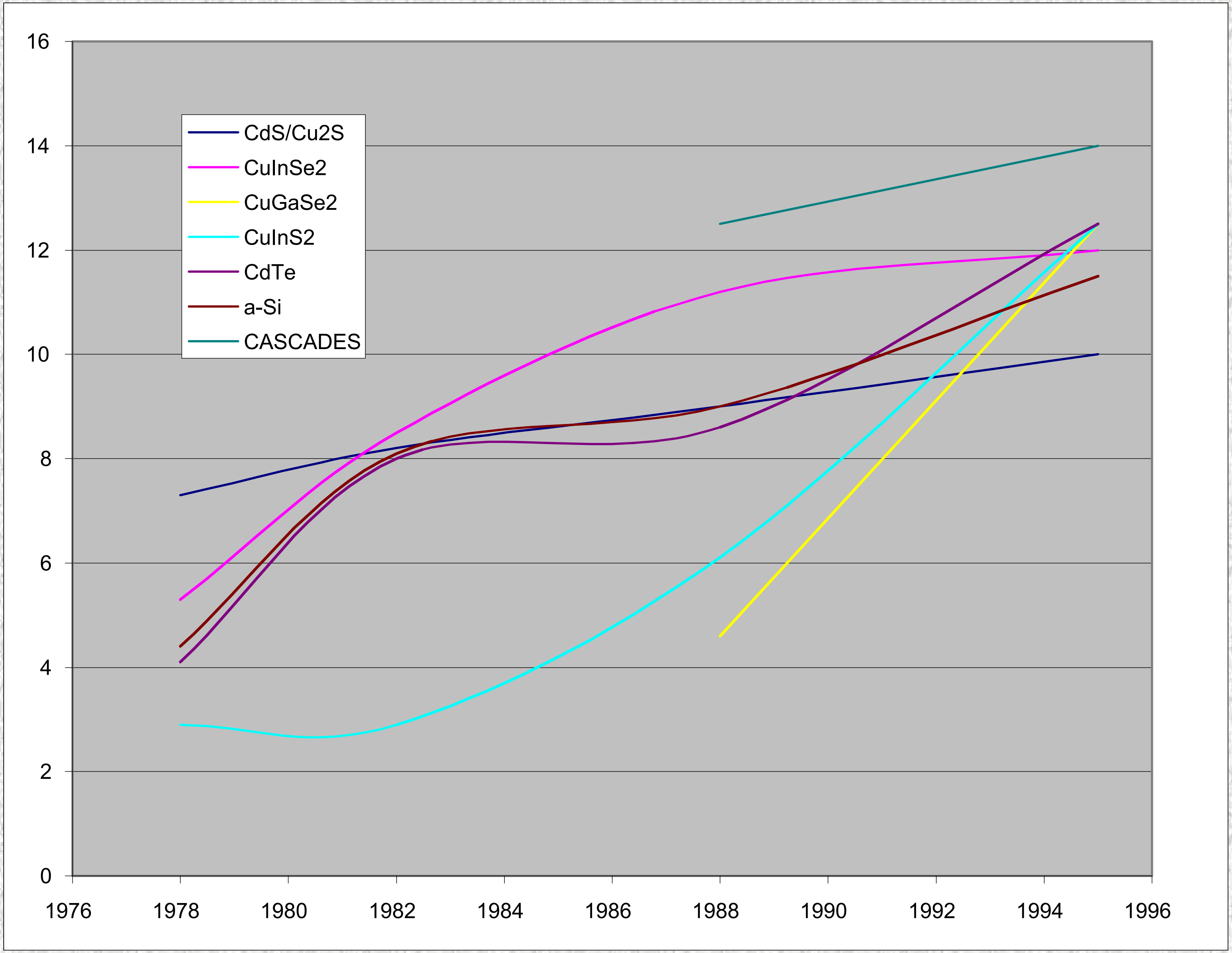
Light Weight: Active material is on the order of 1 to 2 microns thick

Highly Flexible: Ideal for the flexing and motion of a flapping wing

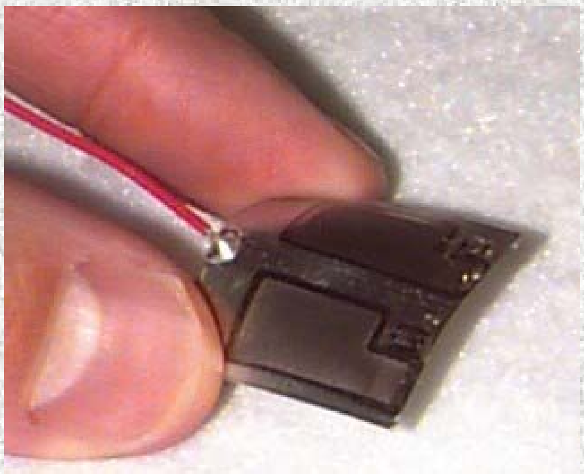
Substrate: Can be made of most materials, presently the best candidate is Kapton (or other polymers). Potentially the Battery or IPMC can be utilized as the substrate

Specific Power: 1 kW/kg near term, 2 kW/kg projected

Thin Film Solar Array Historical Performance Trends



Thin Film Battery/Capacitor Characteristics



ITNES sample battery

•Rechargeable, Lightweight and Flexible

•Configurable in any series / parallel combination

•Rapid charging / discharging capability

•Can be charged / discharged 1000s of times with little loss in capacity

- –Enables long duration flight times

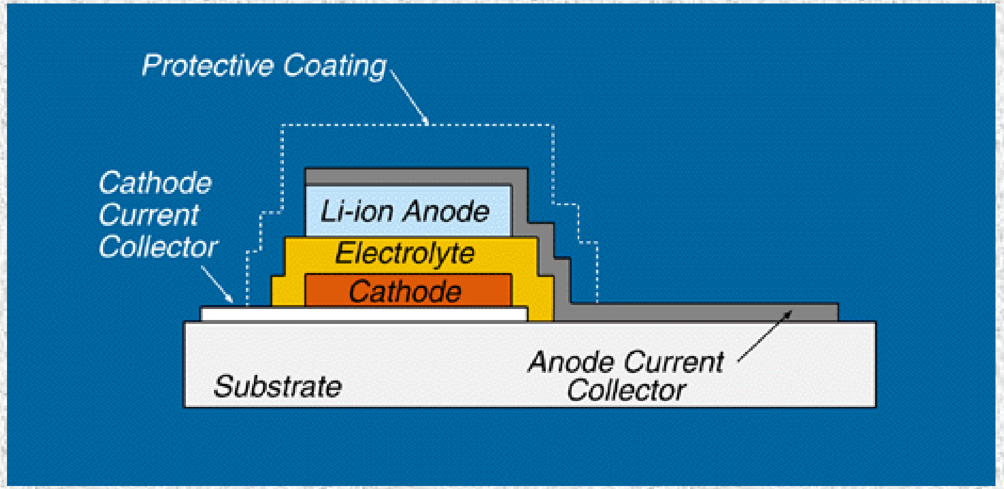
- Long shelf life with little self discharge
  - Ideal for stowage during interplanetary transit
- Operate over a wide temperature range
  - Enables the batteries to operate under various environmental conditions
- The batteries have the capability to provide high pulse currents
  - Ideal for short duration power loading such as flapping the wings

Battery Construction & Operation

Types of Lithium ion thin-film batteries differ in the cathode material they use.

- Ex. Magnesium Oxides, Cobalt Oxides, Yttrium Oxide

The battery is produced by depositing (through sputtering or evaporation techniques) the various material layers that make up the components (cathode, electrolyte, anode and current collector) onto a substrate.



Oak Ridge Battery Design Cross Section (15 micron thick)

Ionic Polymer-Metal Composite (IPMC)

QuickTime™ and a
decompressor
are needed to see this picture.

- This is the core material of the aircraft. It provides the propulsion and control for the vehicle.
- The IPMC material has the unique capability to deform when an electric field is present across it. The amount and force of the deformation is directly related to the strength of the electric field.
- The deformation is not permanent and returns to its original shape once the electric field is eliminated.
- The material can be manufactured in any size and initial or base shape.

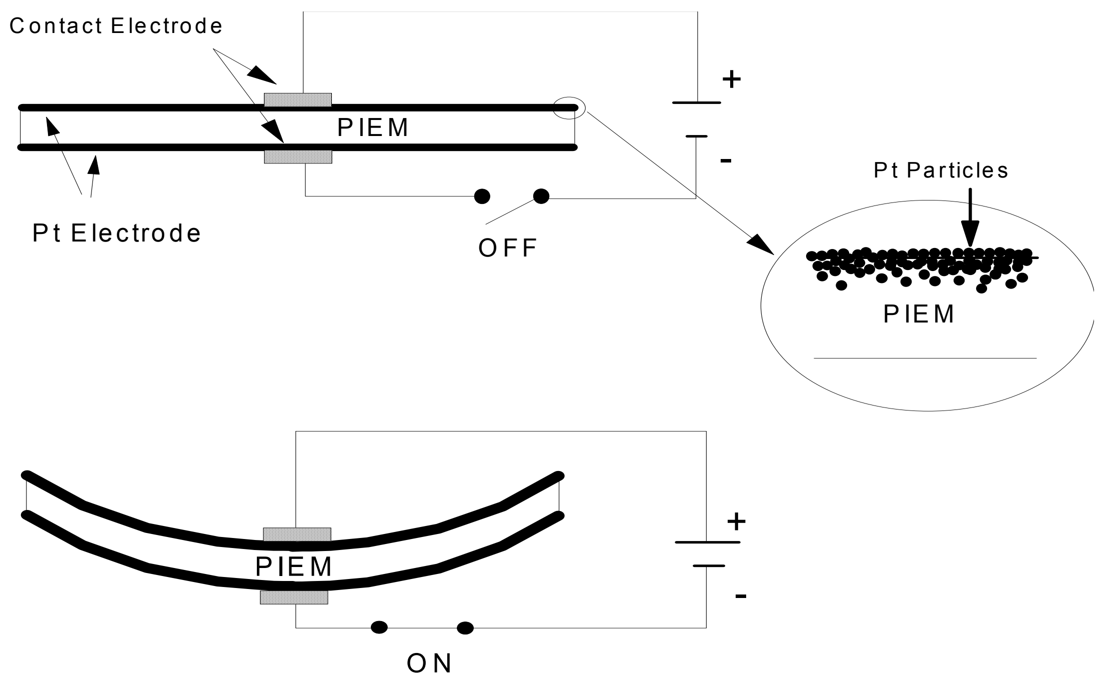
IPMC Material

Constructed of an Ion Exchange Membrane that is surface coated with a conductive medium such as Platinum

Placement of the electrodes can be used to tailor the bending of the material to any shape

Metal Electrodes

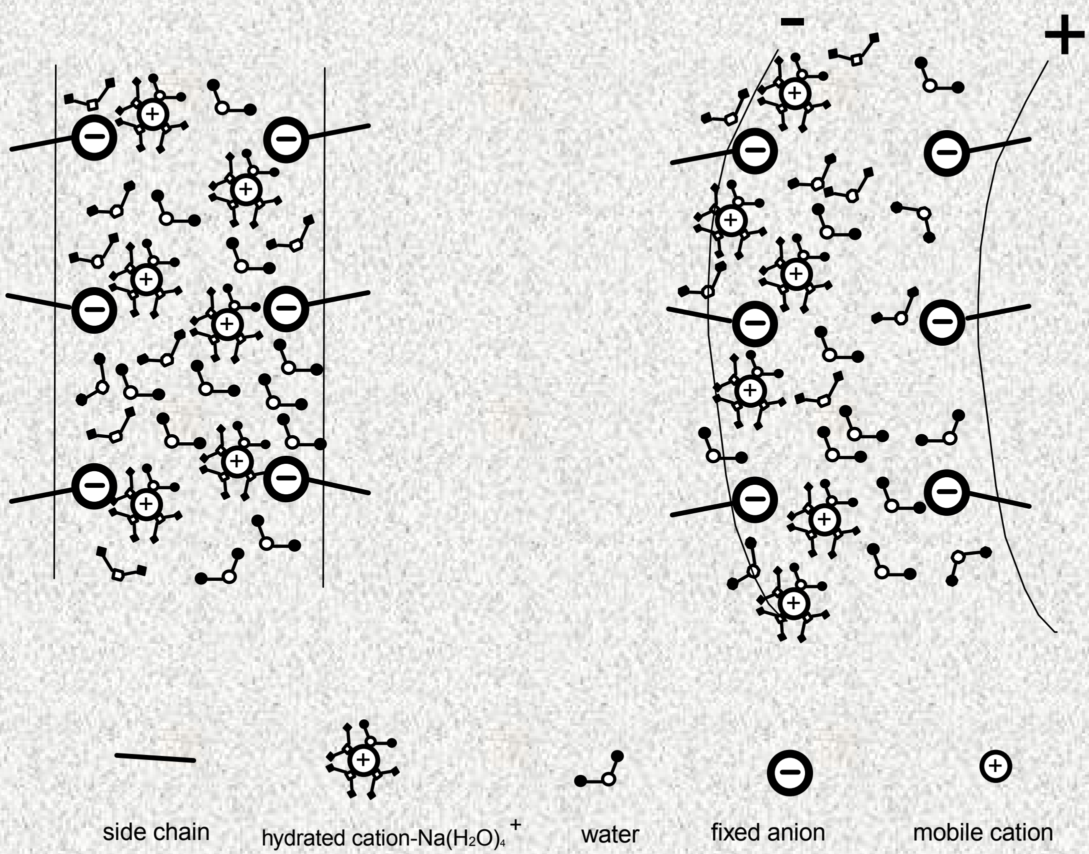
The material will bend toward the anode side of the electrodes



IPMC Motion

Under an electric field the ion exchange membrane
Enables the migration of ions which allows water molecules and
Hydrated cations to migrate toward the negative pole.

This internal movement of water molecules is responsible for creating
Internal strains within the material which enable it to move



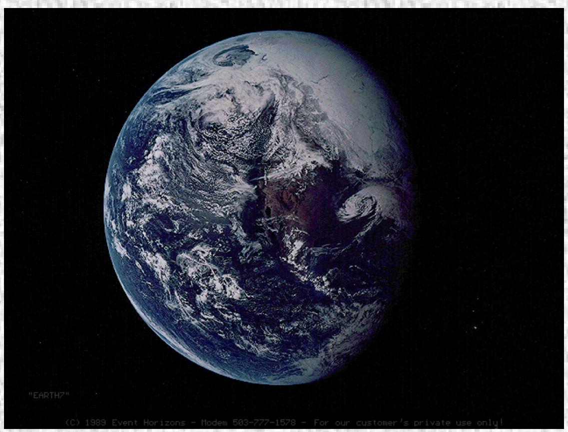
For the IPMC material to operate it must be sufficiently Hydrated

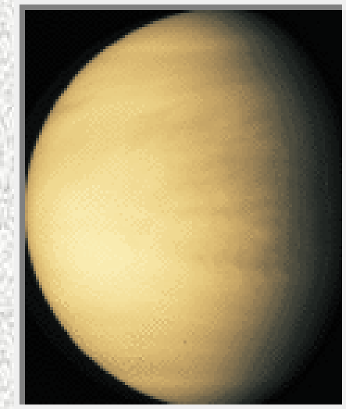
Leakage and operation in dry environments may require sealing or redesign of the material for efficient long term use

IPMC Material Characteristics

Young's Modulus, E	Up to 2 GPa
Shear Modulus, G	Up to 1 GPa
Poisson's ratio, ν	Typical: 0.3-0.4
Power density (W/mass)	Up to 100 J/kg
Max force density (Cantilever Mode)	Up to 40 Kgf/Kg
Max displacement/strain	Up to 4% linear strain
Bandwidth (speed)	Up to 1 kHz in cantilever vibratory mode for actuations Up to 1 MHz for sensing
Resolution (force and displacement control)	Displacement accuracy down to 1 micron Force resolution down to 1 mg
Efficiency (electromechanical)	Up to 6 % (frequency dependent) for actuation Up to 90% for sensing
Density	Down to 1.8 g/cm^3

Solid State Aircraft Applications



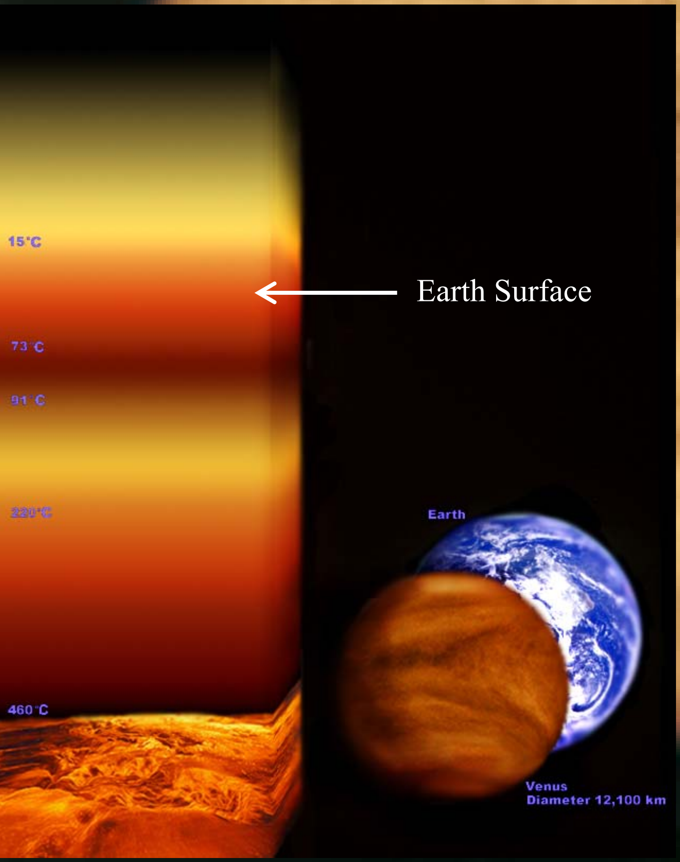


There is sufficient solar intensity for this aircraft to operate on Earth, Venus or Mars

Because of its projected relatively small mass and flexibility, the aircraft is ideal for planetary exploration. These characteristics allow the aircraft to be easily stowed and launched at a minimal cost. Potentially, a fleet of these aircraft could be deployed within a planet's atmosphere and used for comprehensive scientific data gathering, as an quickly deployable quiet observation platform or as a communications platforms.

Venus Environment

- **Rotation Period (Day) of Venus is Longer the Revolution Period (Year) Potentially Enabling Continuous Flight**



- **Atmosphere is mainly Carbon Dioxide (96.5%) Also contains trace amounts of corrosive Compounds (Hydrochloric, hydrofluoric & Sulfuric Acids)**
- **Atmospheric Density Equals Earth Surface Density at ~50 km**
- **Incident Solar Intensity is ~2600 W/m^2**
- **Very high wind speeds above the cloud tops ~ 100 m/s**
- **Clouds On Venus Extend Upwards to ~64 km**

Mars Environment

- The atmosphere on Mars is very thin. At the Surface the density is similar to 30 km on Earth
- The atmosphere is composed mostly of Carbon Dioxide

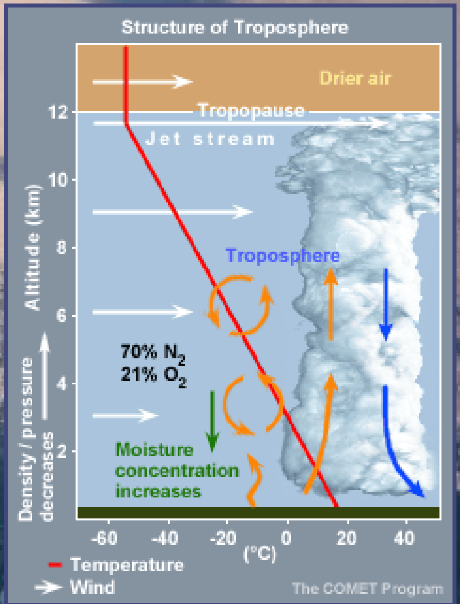
- The temperature on Mars is on average much colder then on Earth Although at certain times of the year and locations the temperature will rise above freezing, most of the time temperatures are well below the freezing point of water.
- The gravitational force on Mars ($3.57\ m/s^2$)is about 1/3 what it is on Earth.
- Solar intensity at Mars is ~590 W/m^2
- There are few clouds but dust storms are fairly common

Earth Environment

- Gravitational Force 9.81 m/s^2
- Solar Intensity 1352 W/m^2
- Atmospheric composition is approximately 80% Nitrogen, 20% Oxygen

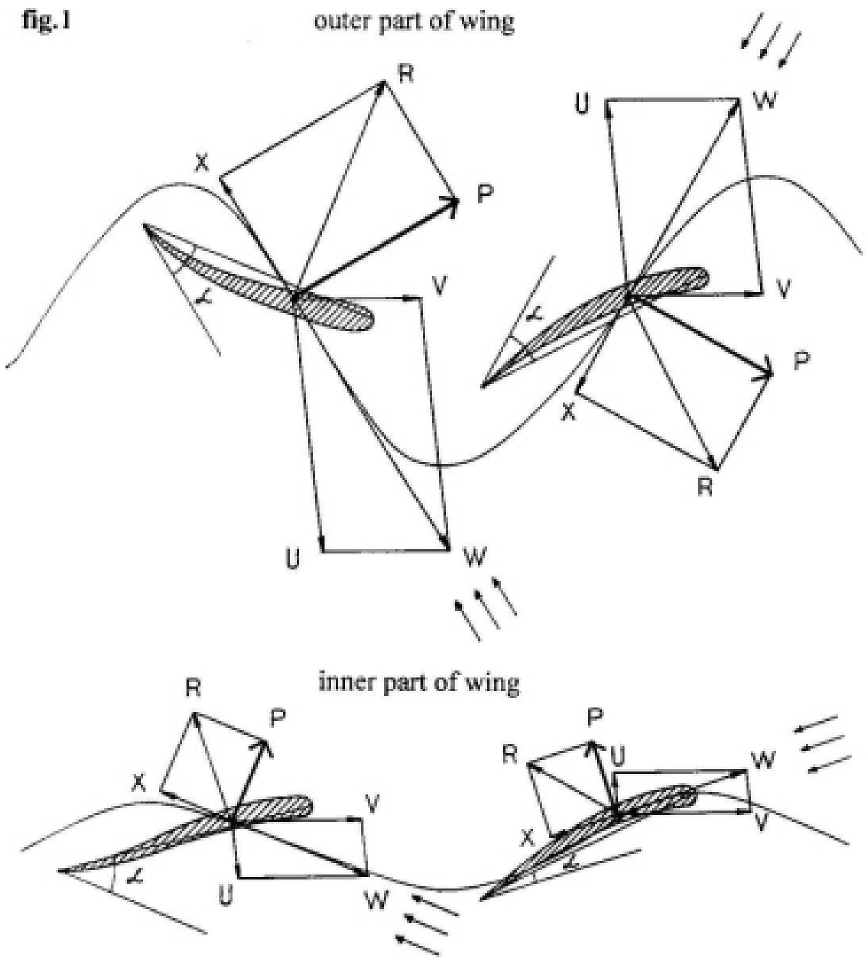
Wind speeds generally increase from the surface up to a maximum around the top of the Troposphere (Jet Stream)

The majority of Earth's weather occurs within the Troposphere which extends to approximately 12 km



Lift and Thrust Generation

The propulsion force and lift generation of the aircraft are accomplished by the flapping of the wings.



By altering the shape and angle of attack of the wing the amount of lift and the direction of this lift force can be controlled

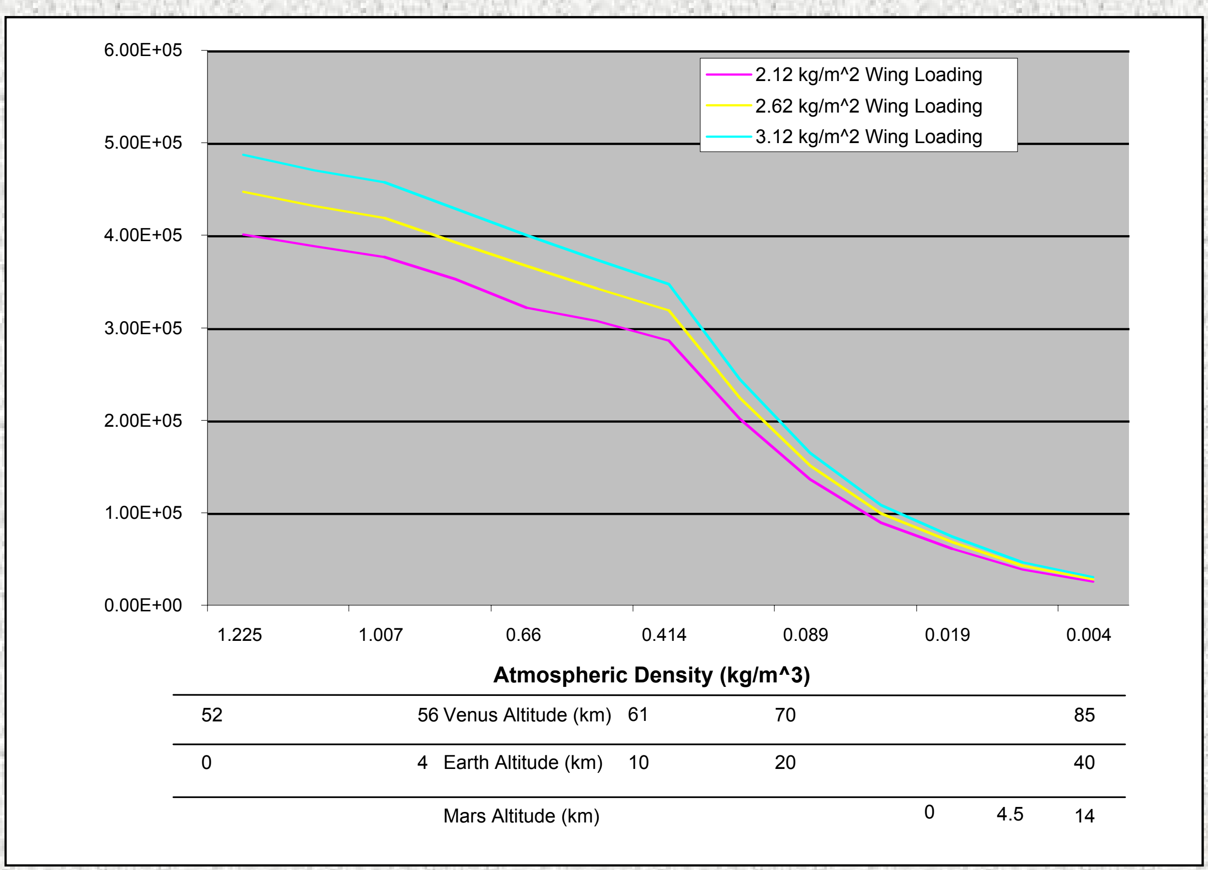
This is the same method birds use to generate lift and thrust

The lift and lift vector generated can Vary between each wing as well as along the wing span itself.

This provides a significant amount of control and provides a means for maneuvering

Wing Aerodynamics

Like all flapping wing flyers in nature the solid state aircraft will operate within a low Reynolds number flight regime. This is due mainly to its required low wing loading and the potential for high altitude operation, where the air density is low.



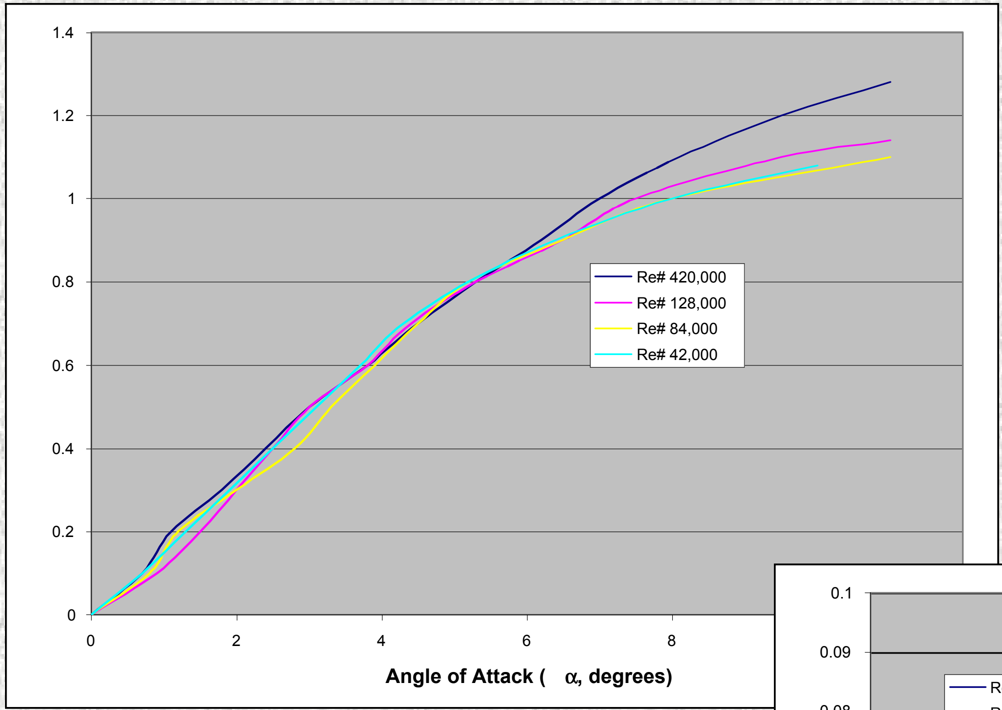
$$R_e = \frac{\rho V c}{\mu}$$

Wing Assumptions:

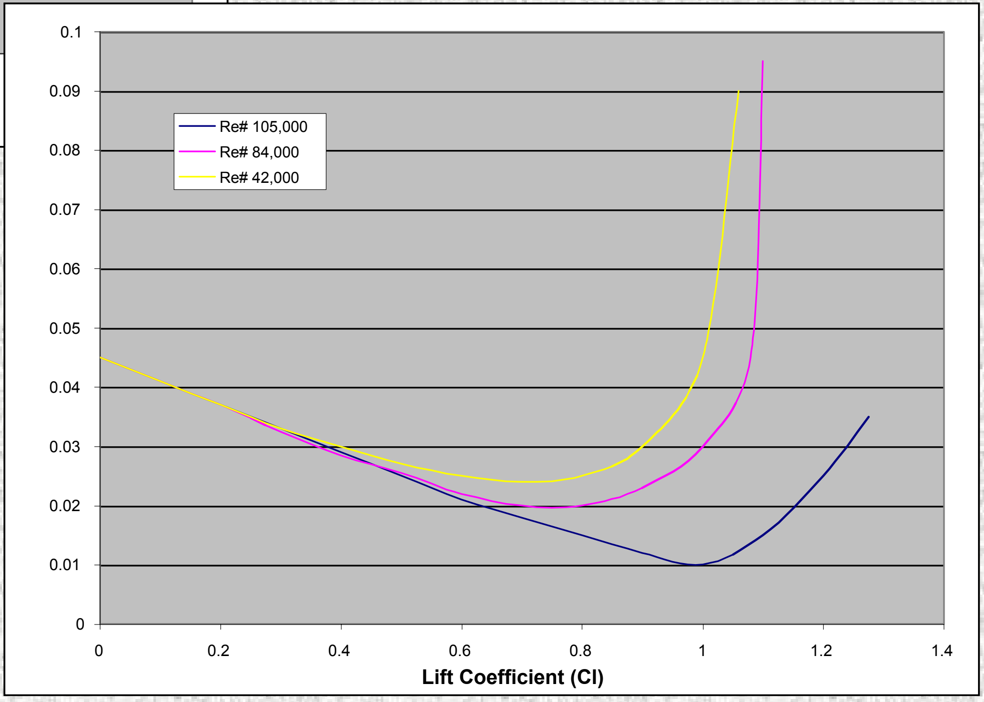
Curved flat plate airfoil
Rectangular wing planform

These are conservative estimates. Wing and aircraft performance can be increased by optimizing the wing design for a specific flight regime.

Effect of Re# on Aircraft Performance

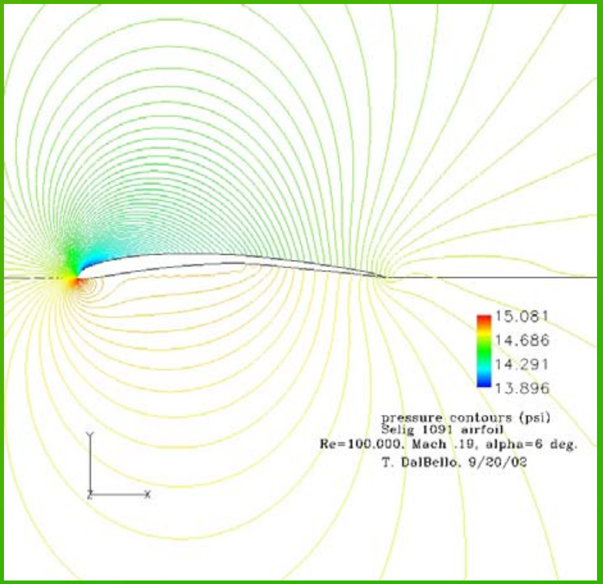


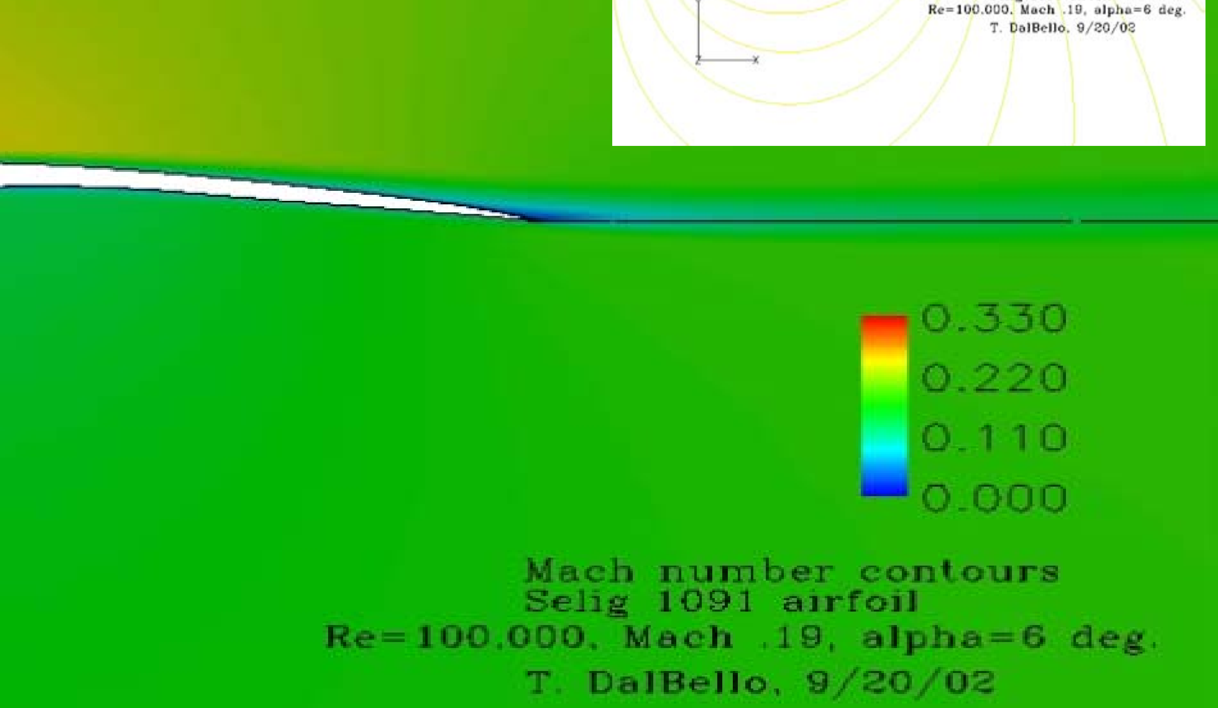
Flight Reynolds number based on chord length for a flat plate airfoil

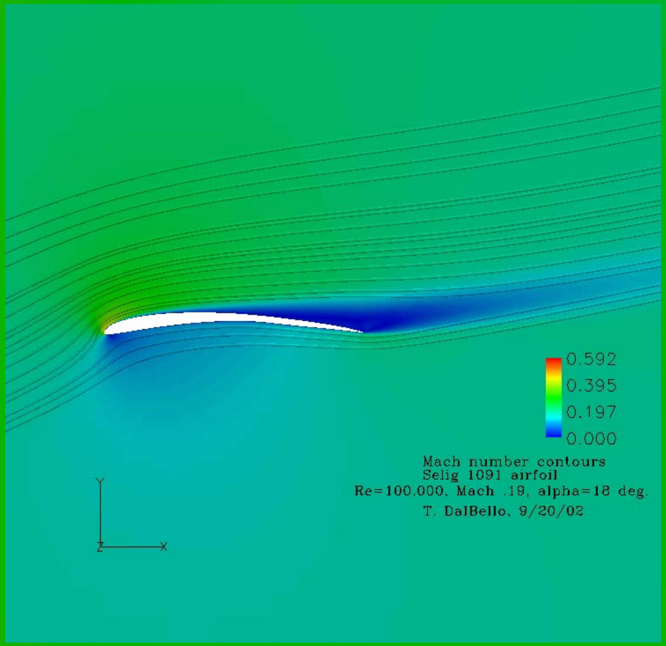


CFD Airfoil Analysis

CFD analysis is ongoing to provide lift coefficient and drag coefficient data for a thin curved airfoil at Angles of attack and Reynolds numbers representative Of the estimated SSA flight regime and wing motion

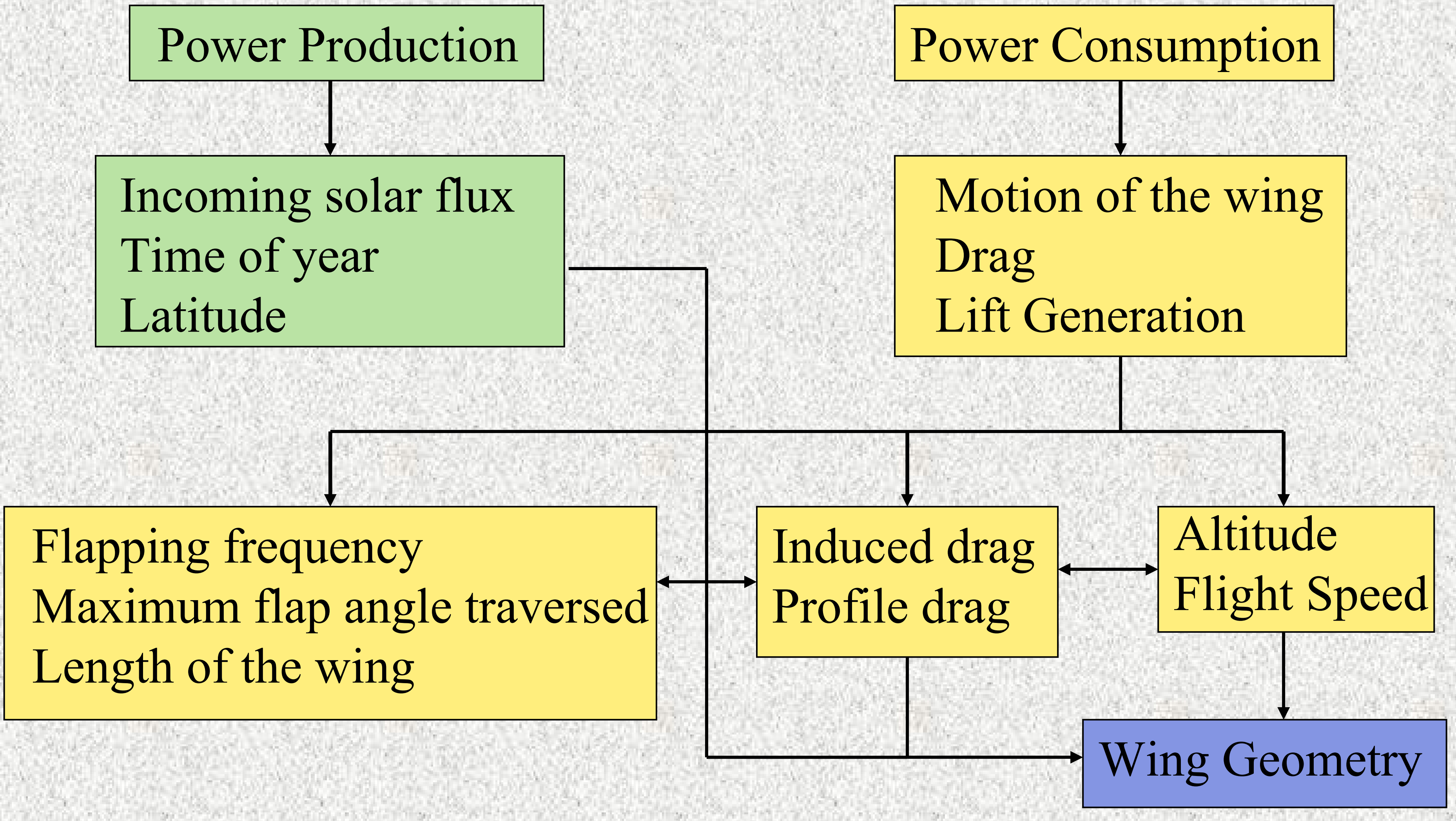






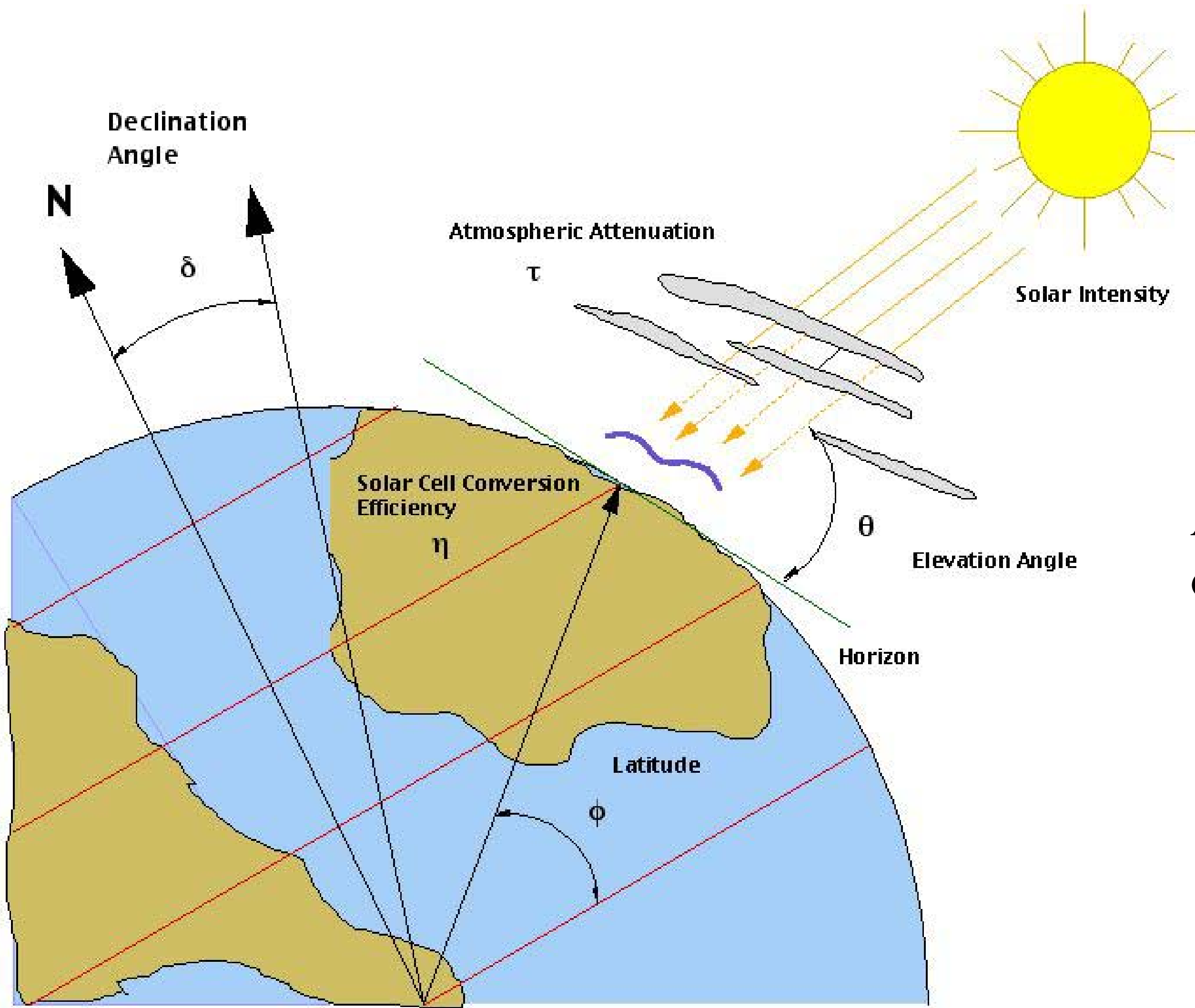
Sizing Analysis

An analysis was performed to determine the feasibility of the SSA concept and establish the range of operation on the planets of interest.



Power Production

The amount of power available to the aircraft is based on the Environmental conditions it is flying within



Output power will vary based on the

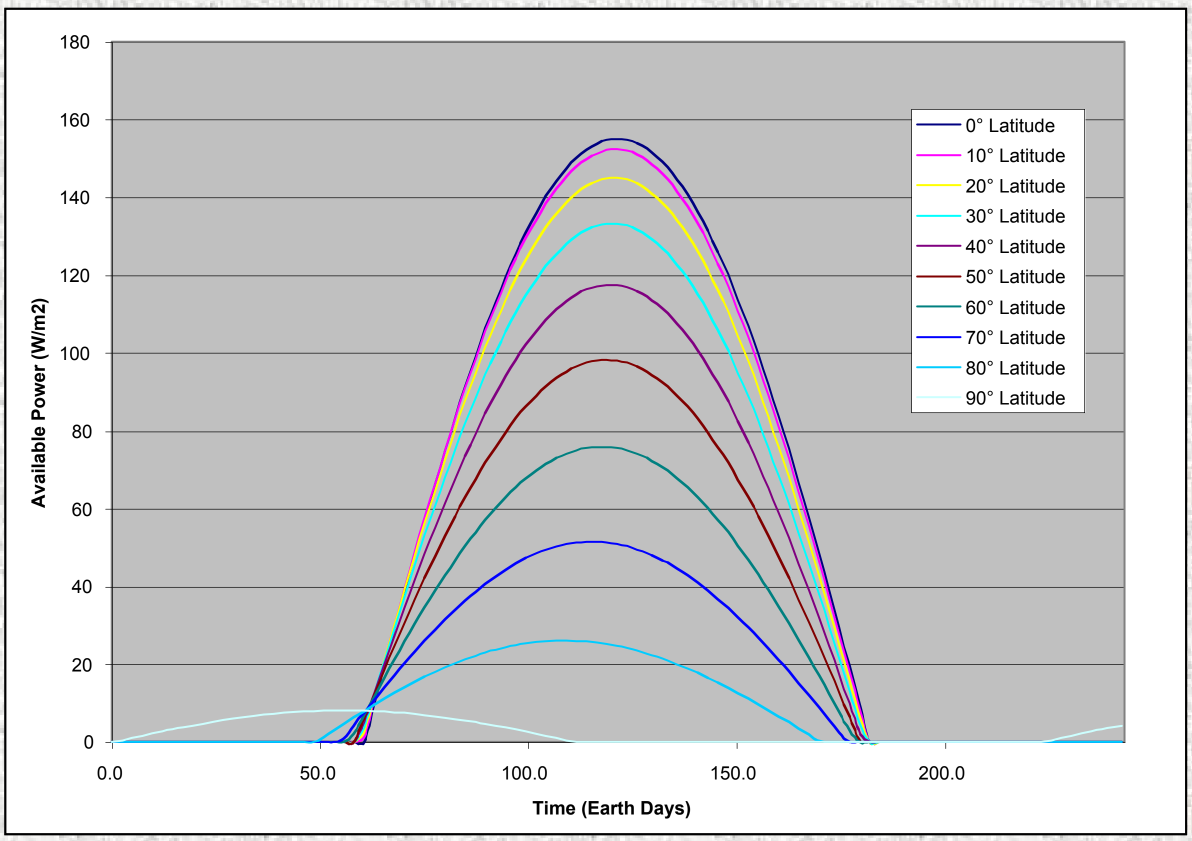
- Latitude of flight (ϕ)
- Time of year (δ)
- Time of day (θ)

Available power also depends on the

- Atmosphere attenuation (τ)
- Solar cell efficiency (η)

Power Production: Venus

There is no variation between daily and yearly power profiles because of the very long day length (equal to 263 Earth days) which is longer then the Venus year (equal to 244 Earth days)

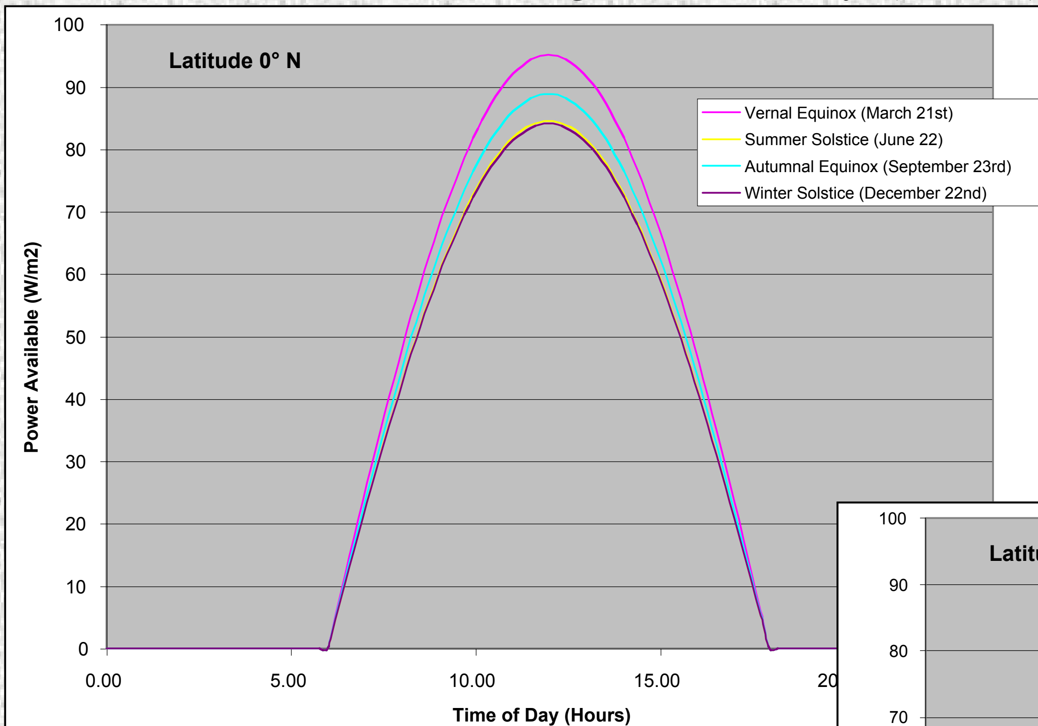


- Solar cell efficiency 10%
- Solar cell fill factor 80%
- Horizontal solar array
- Atmospheric Attenuation 25%
- Mean Solar Intensity above atmosphere 2620 W/m^2
- Longitude 0°
- Maximum declination angle 3°

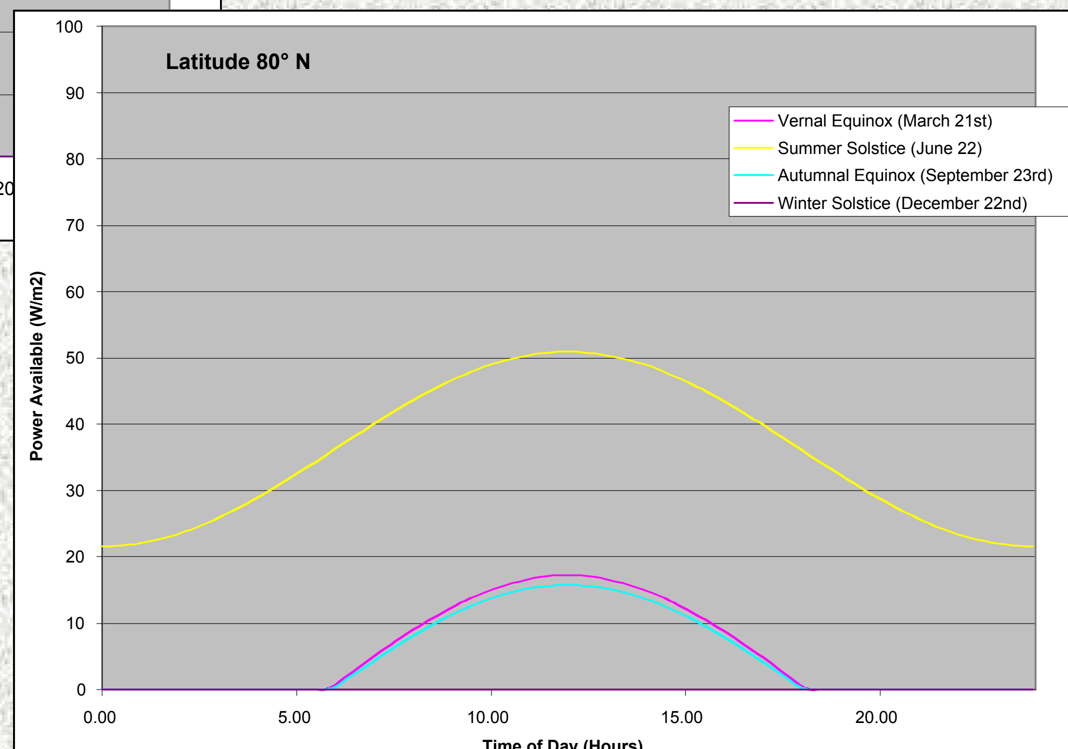
Available Power Throughout A Day (Earth Days)

Power Production: Earth

Available Power Throughout the Day (Hours)



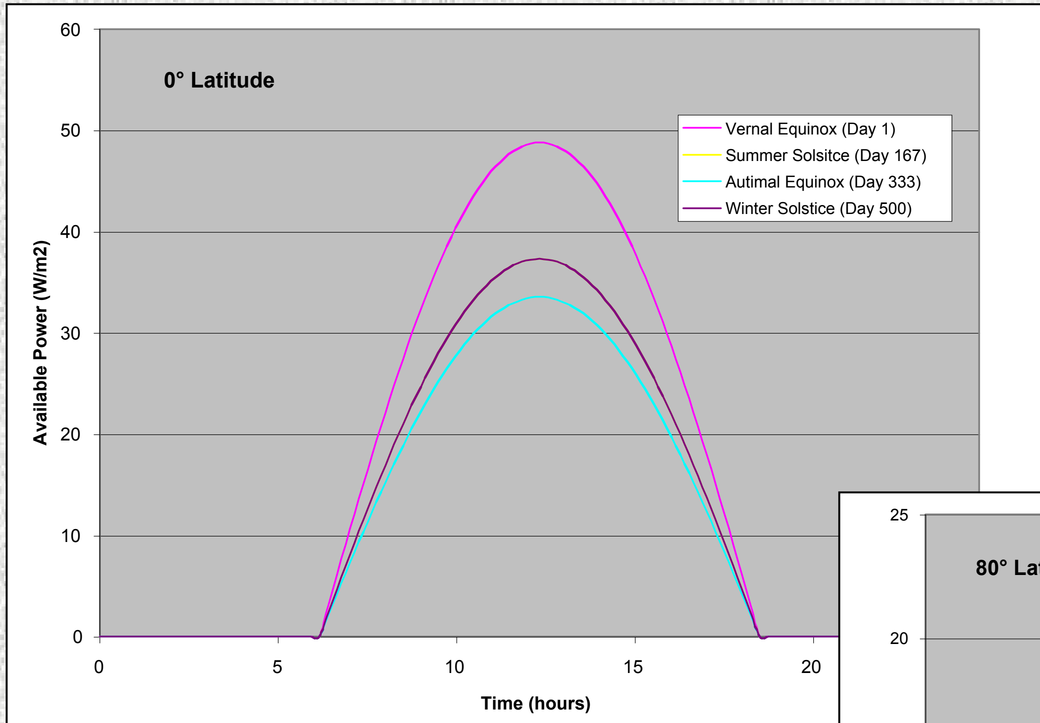
- Solar cell efficiency 10%
- Solar cell fill factor 80%
- Horizontal solar array
- Atmospheric Attenuation 15%



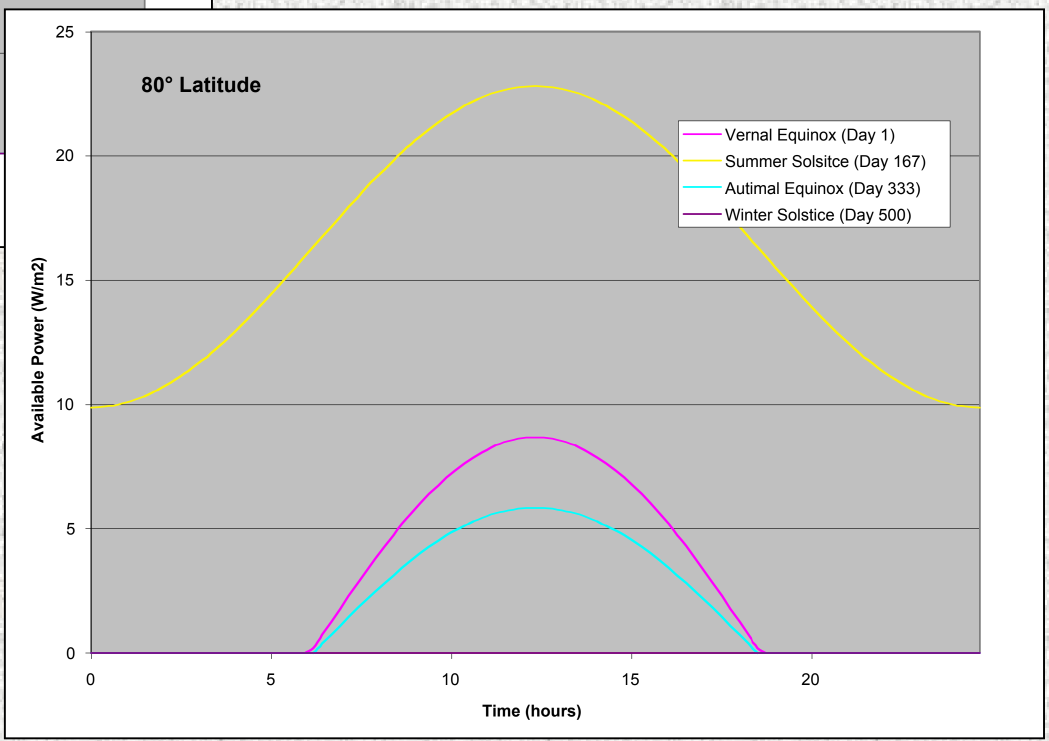
- Mean Solar Intensity above atmosphere 1353 W/m^2
- Longitude 0°
- Maximum declination angle 23.5°

Power Production: Mars

Available Power Throughout the Day (Hours)



- Solar cell efficiency 10%
- Solar cell fill factor 80%
- Horizontal solar array
- Atmospheric Attenuation 15%

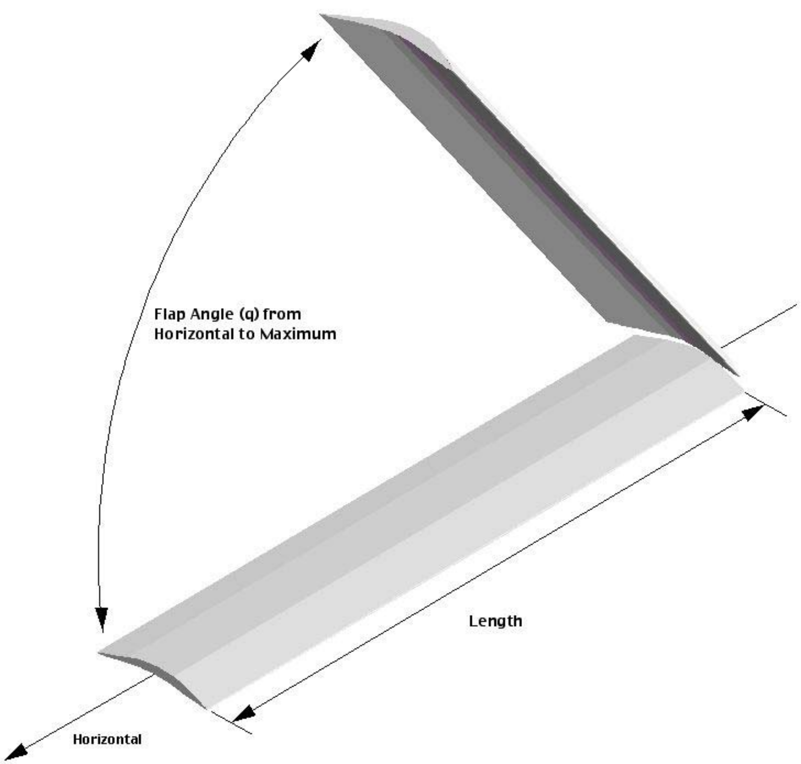


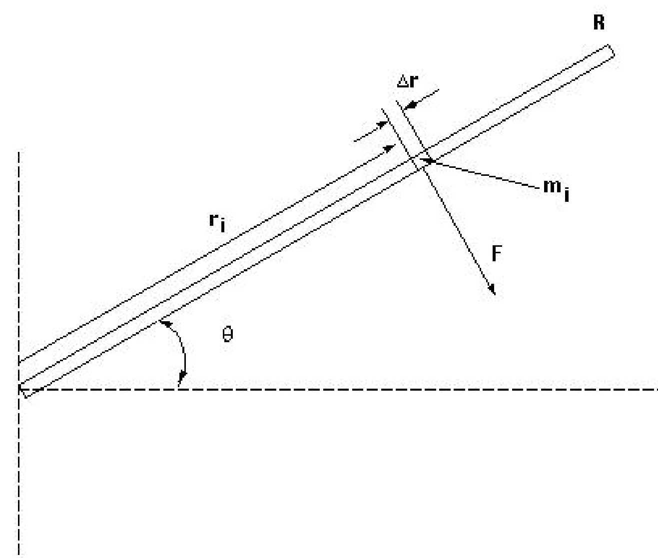
- Mean Solar Intensity above atmosphere 590 W/m^2
- Longitude 0°
- Maximum declination angle 24°

Power Consumption due to Motion

Motion of the wing consists of a flapping rate and maximum angle traversed during the flap

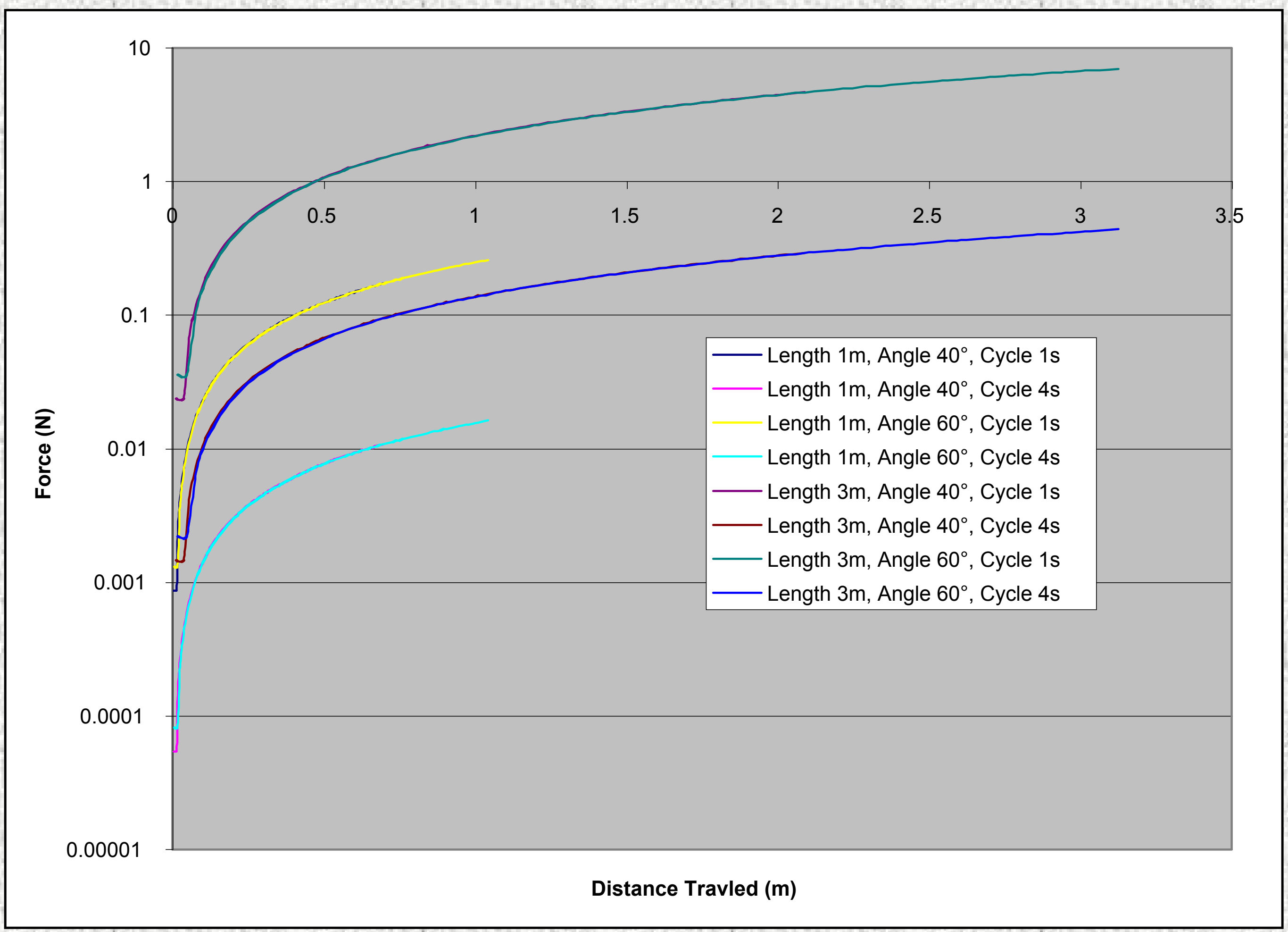
The forces generated by the wing motion are due to the acceleration and deceleration of the wing mass. These forces vary along the wing length





Wing Force Due to Motion

Force versus Distance Traveled for Various Wing Lengths, Maximum Flap Angles and Flap Frequencies

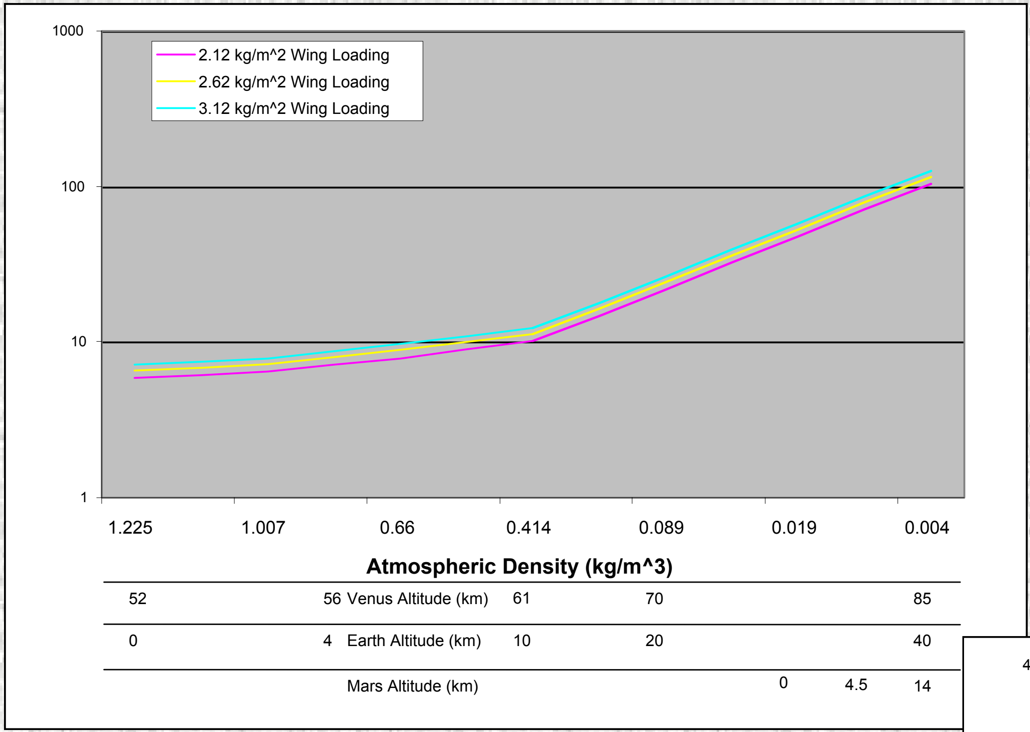


The power required to move the wing is the area under the force vs distance traveled curve.

The distance traveled varies along the wing length to a maximum at the tip.

Power consumption can be reduced by tapering the wing so there is less mass at the tip. Thereby reducing the force needed for motion.

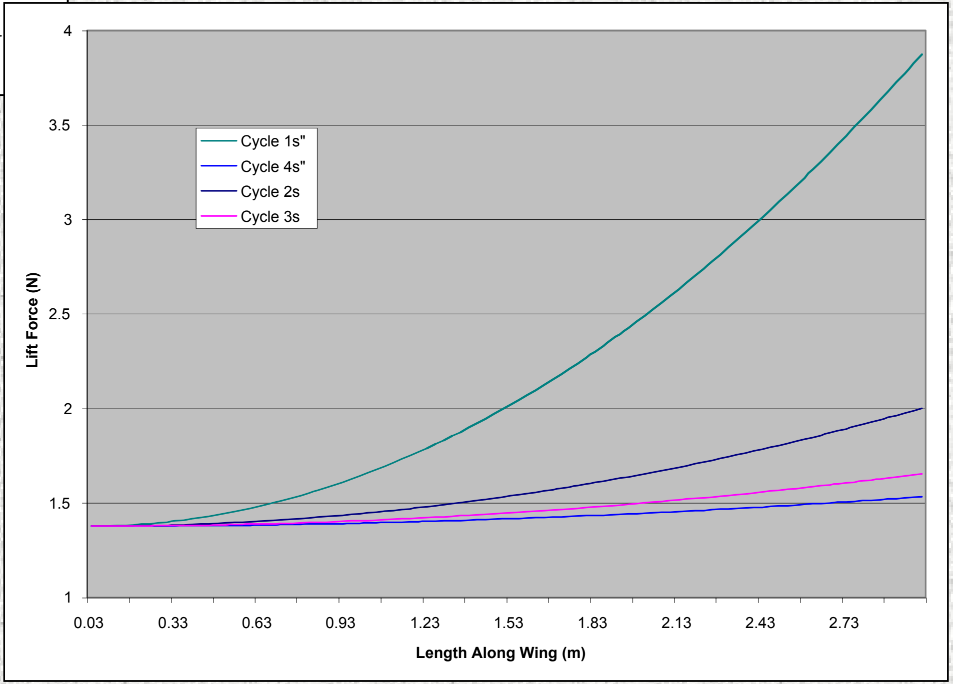
Drag Due to Lift and Velocity



The aerodynamic drag is due to the generation of lift and the movement of the aircraft through the atmosphere

$$D_f = \sum_{0}^{i} \frac{1}{2} \rho V_i^2 (c_f 2S + c_d S)$$

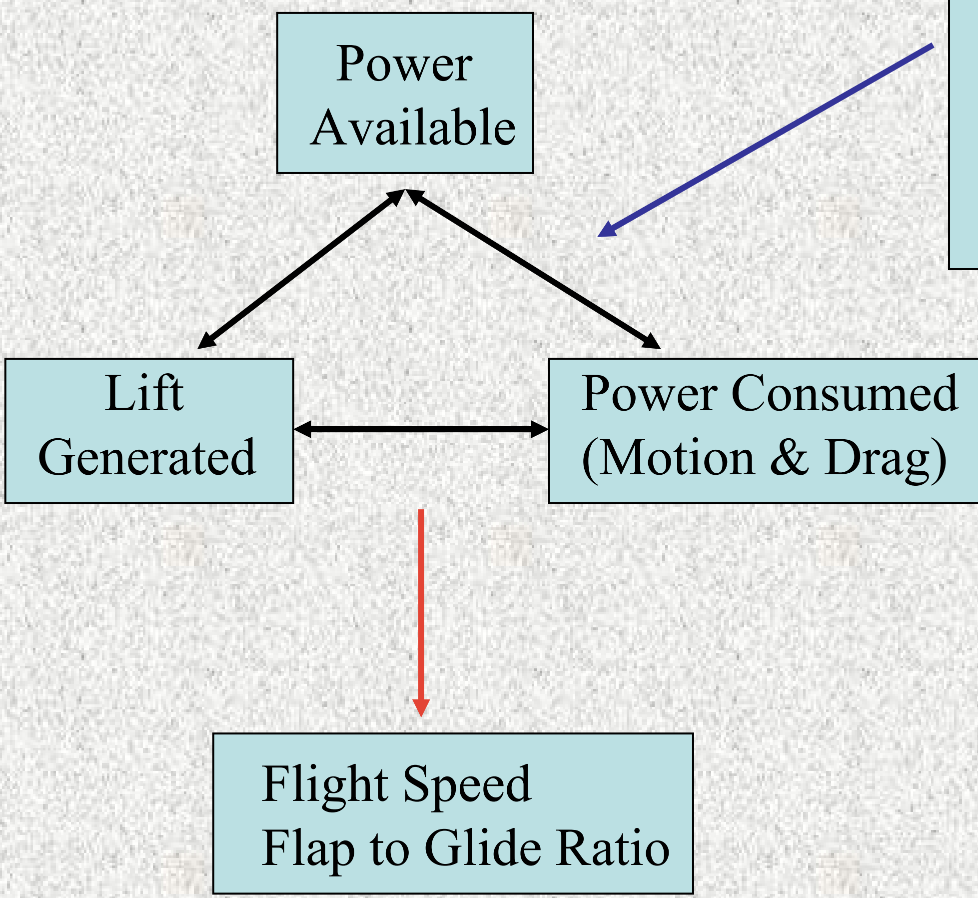
The drag is dependent on the flight velocity which in turn sets the lifting capacity and the lift to drag characteristics of the airfoil.



Analysis Method

The energy consumed during the flap has to equal the energy collected during the total flap and glide cycle.

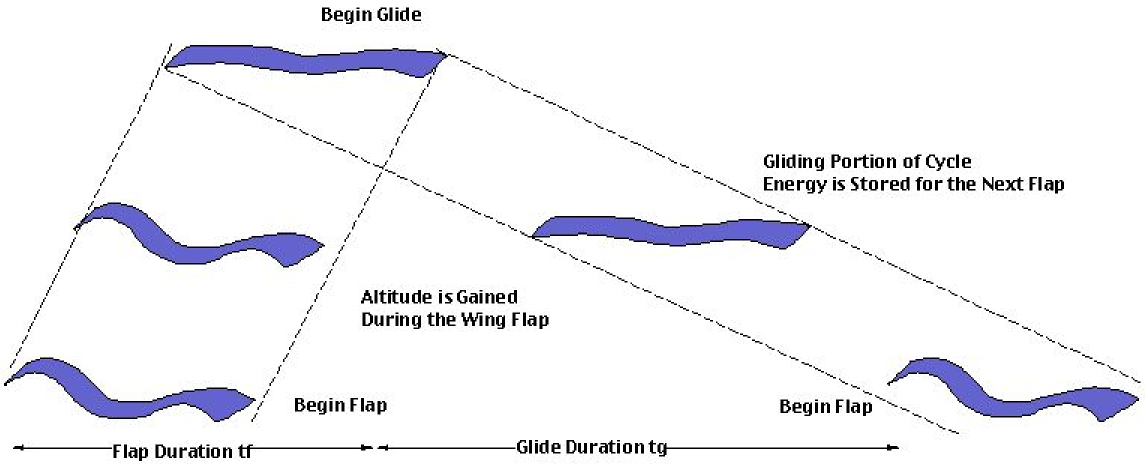
Inputs
Flapping Frequency
Flap Angle
Aircraft Size
Altitude

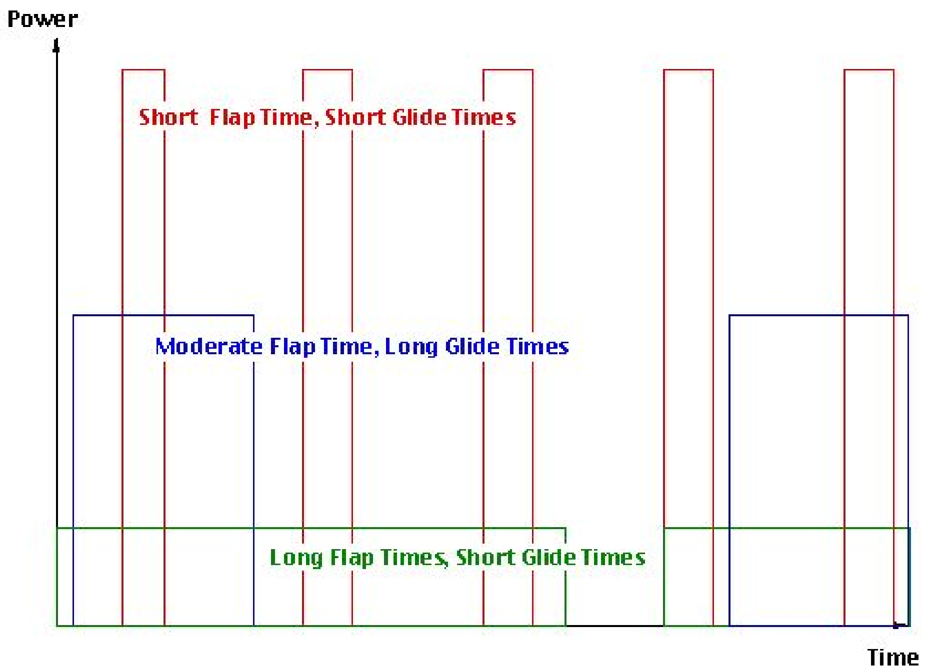


- The analysis was an iterative process
- For a given set of inputs the flight speed and flap to glide ratio would be calculated.
- If no solution existed then certain inputs would be varied until a solution was found.

Operational Scheme

•The aircraft will fly in a manner similar to an Eagle or other large bird.
•The aircraft will glide for extended periods of time and flap its wings periodically to regain altitude and increase forward speed.





The ratio of glide time to flap time will depend on the available power, power consumption and flight conditions.

The analysis was performed to determine the optimal glide to flap ratio for a give aircraft configuration under a specific flight condition

Aircraft Sizing

The initial feasibility study was performed to determine the capabilities of the aircraft under the environmental conditions of the planets of interest.

This initial analysis was based on the following assumptions

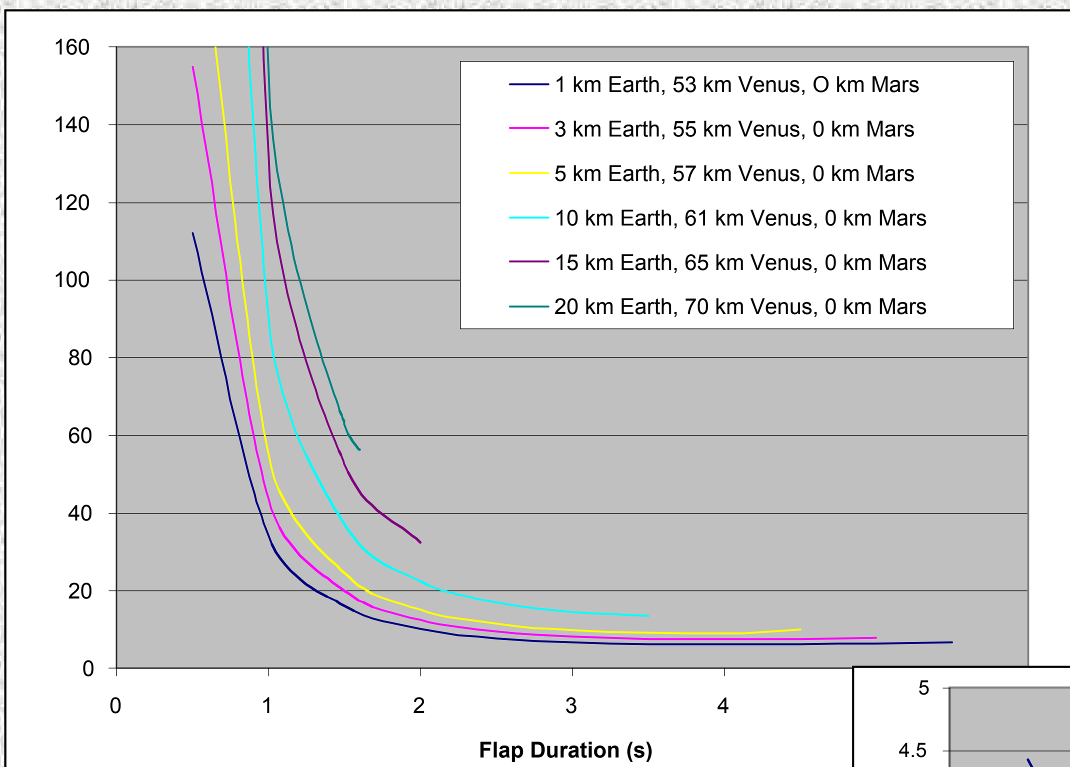
Wing Loading	3.12 kg/m^2
Aspect Ratio	8
Wing Friction Coefficient	0.008
Maximum Flap Angle	45°
Solar Cell Efficiency	10%
Solar Cell Specific Mass	0.12 kg/m^2
Battery Specific Mass	0.75 kg/m^2
IPMC Specific Mass	2.00 kg/m^2
Payload Specific Mass	0.25 kg/m^2

Potential flight altitude ranges investigated in the analysis for each of the planets of interest

Venus	53 km to 82 km
Earth	1 km to 35 km
Mars	1 km to 7 km

Sizing Results

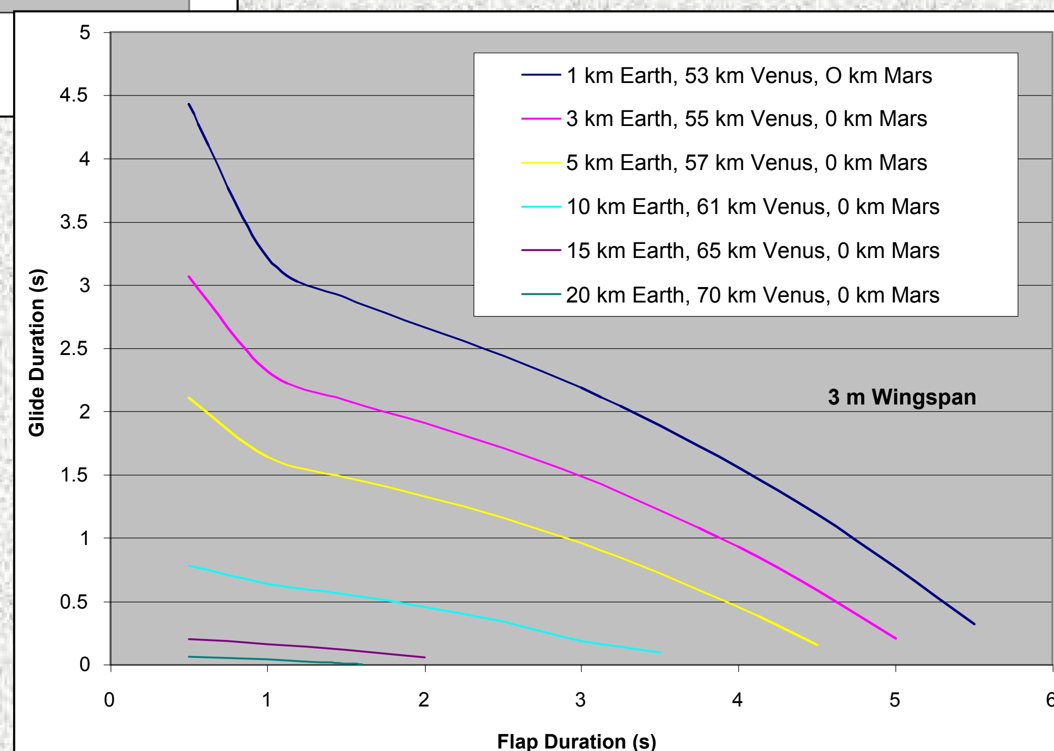
3 m Wingspan SSA



Required power in W/m² of wing area were generated for a range of flap durations over a number of altitude levels

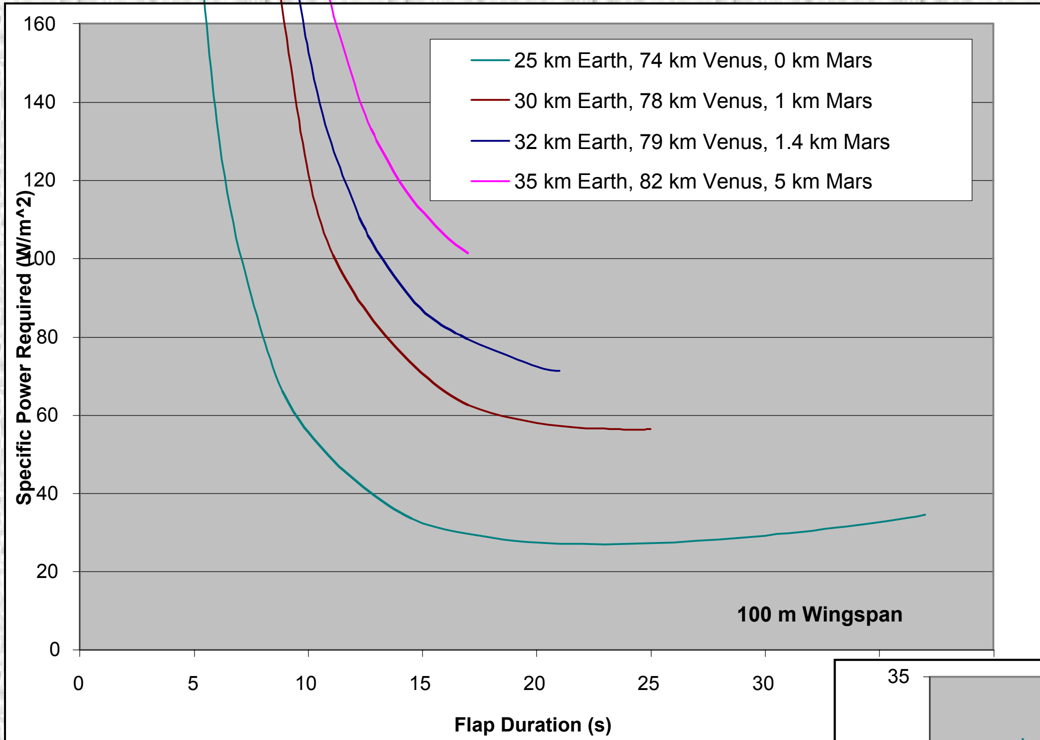
Form the curves it can be seen that for a given size aircraft there is a flap duration that produces a minimum required specific power.

The minimum specific power occurs at smaller flap durations (higher flapping frequencies) as the flight altitude is increased.



Sizing Results

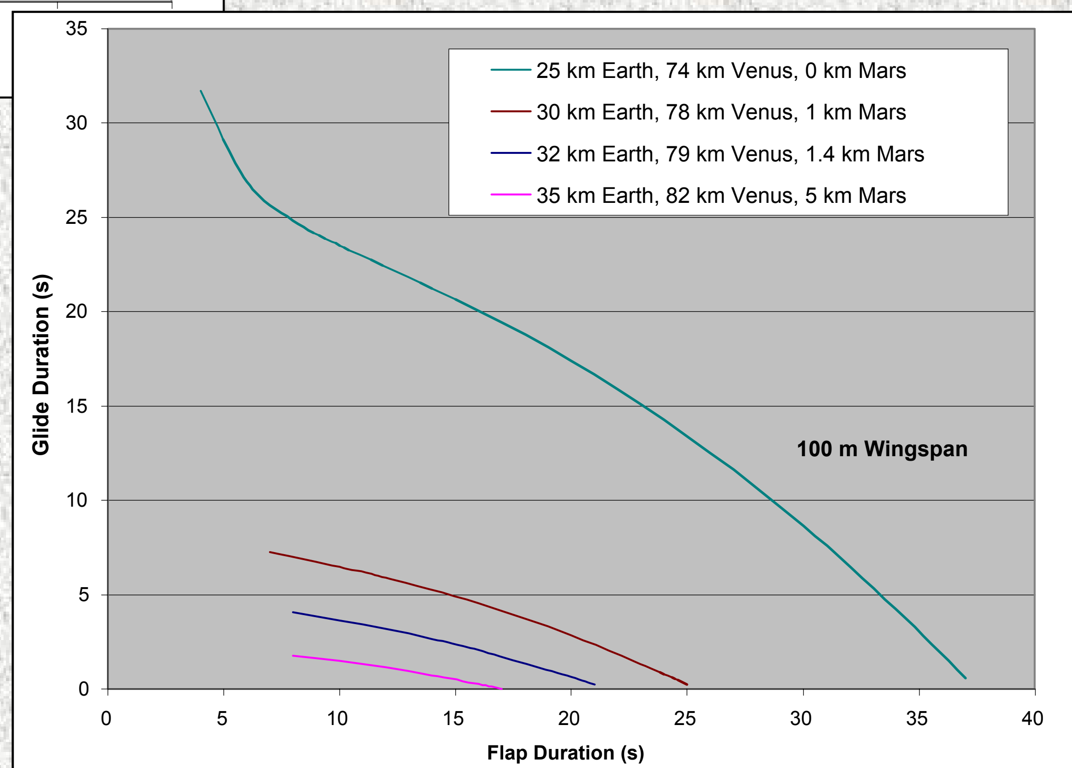
100 m Wingspan SSA



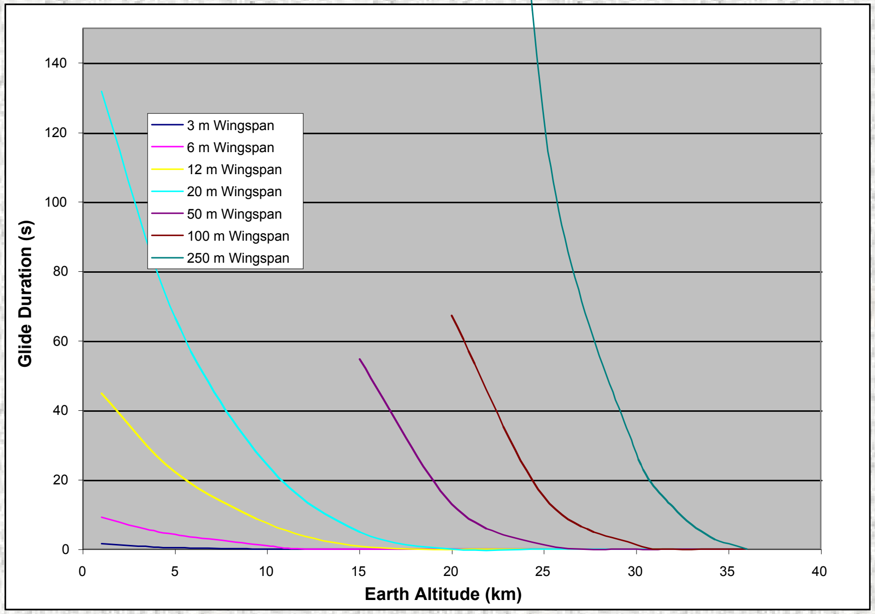
As the altitude increases the vehicle must flap more frequently or continuously to maintain flight.

For all vehicle sizes the glide duration decreases with increasing altitude

As the flap duration increases (lower frequency) the glide duration approaches zero



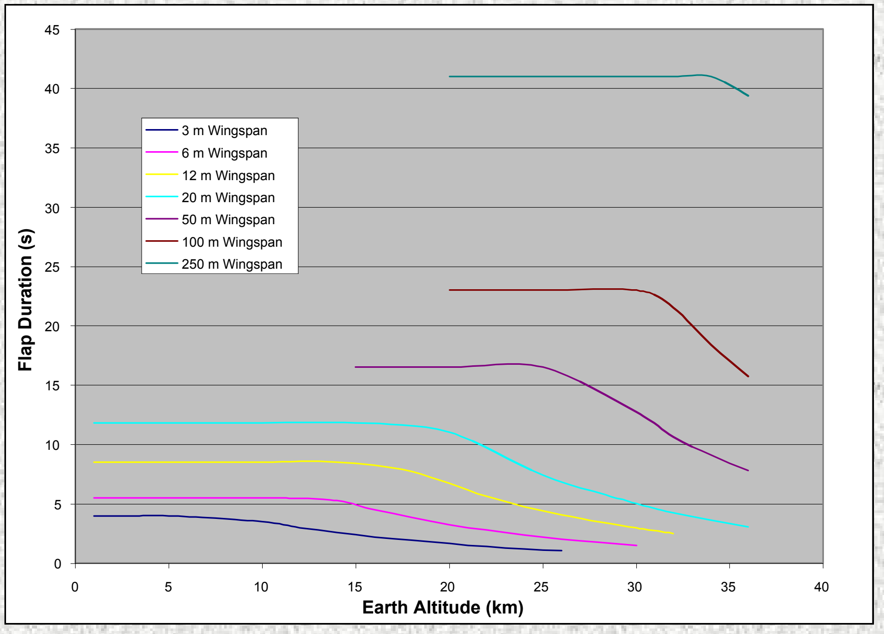
Sizing Results Optimal Operation



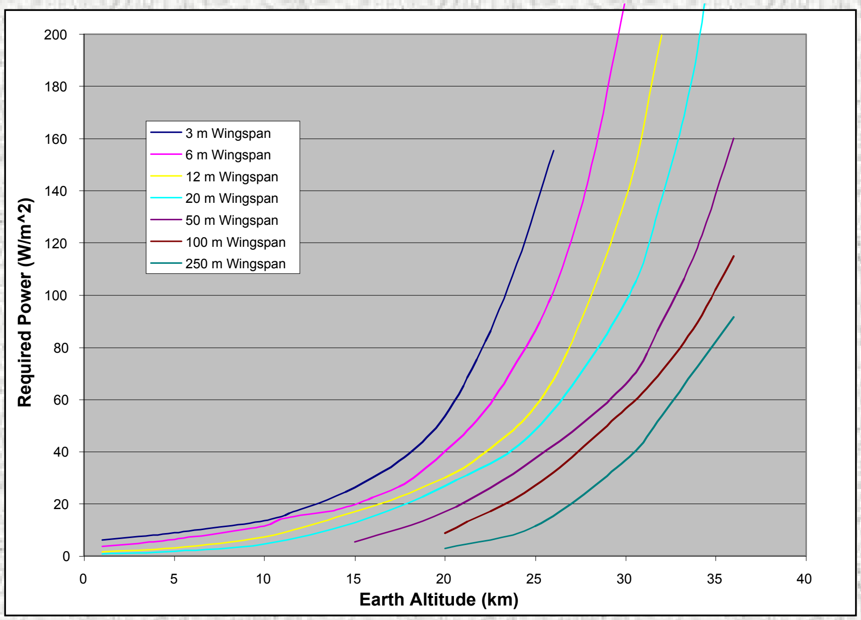
Glide duration goes to zero with increasing altitude

Flap duration, Glide Duration and Required Power as a Function of Altitude (Earth) for Various Size Aircraft

Graphs shown are based on the flap duration that produced a minimum required power for a given size aircraft and flight altitude

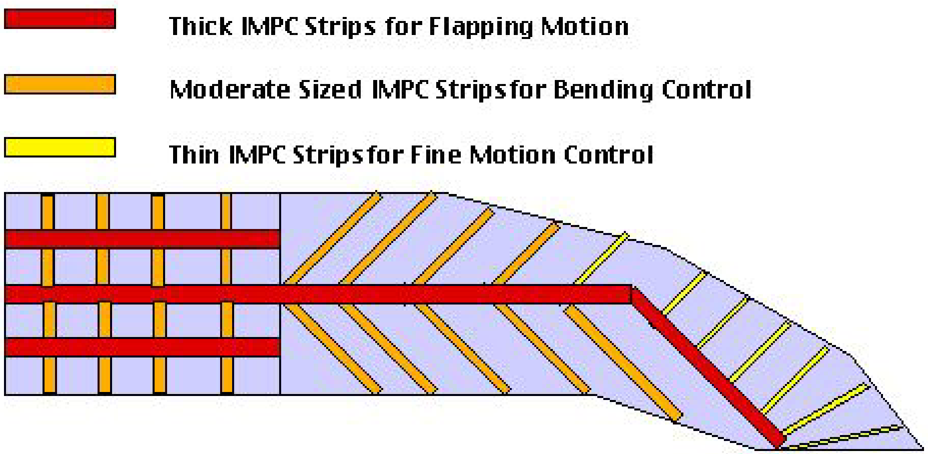


Flap duration remains constant until the glide Duration reaches zero then begins to decrease



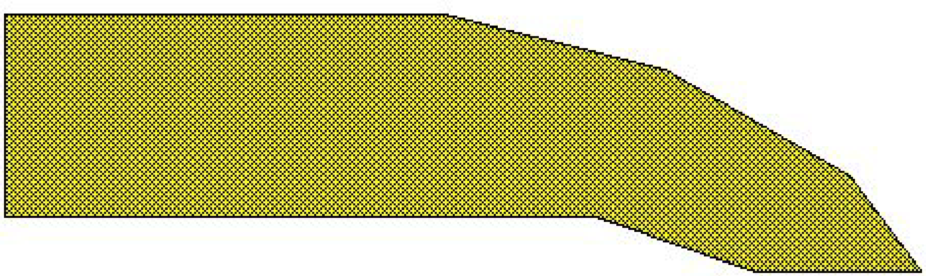
Required power increases exponentially with increasing altitude

Internal Configuration Options



Strips of Various Thickness IPMC Material Attached Via a Skeleton Like Structure

- •Skeletal structure where strips of IMPC Material are used to produce motion by contracting
- •Limits control but may be lighter and stronger then the continuous sheet option

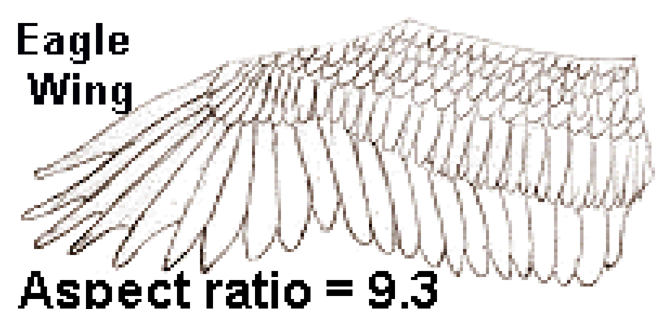


Continuous Sheet of IPMC with a Fine Electrode Mesh for Infinate Shape Control

- •Continuous Sheet of IMPC with electrode gird
- •Provides very fine control of motion

Nature Inspired Configuration

- The Pteranodon is the largest animal that ever flew.
- It is the closest in size, weight and wing span to the SSA
- As an initial starting point for a more detailed wing design the Pteranodon wing will be used as the model (nature has a way of finding the optimum)



Future Plans

– ***Key Items to Further Develop the SSA Concept***

- Construct a small (~.5 m) wing section and demonstrate the operating principle of the vehicle
  - Integration of Photovoltaic array and IMPC
  - Establish a control scheme of wing motion
- Perform a detailed wing and airfoil design optimized for flapping flight under the specified operational Reynolds number
  - CFD and wind tunnel validation
- Perform a more detailed system study
  - Examine variations in wing geometry, operation conditions and component masses
  - Evaluate mission potential & payload