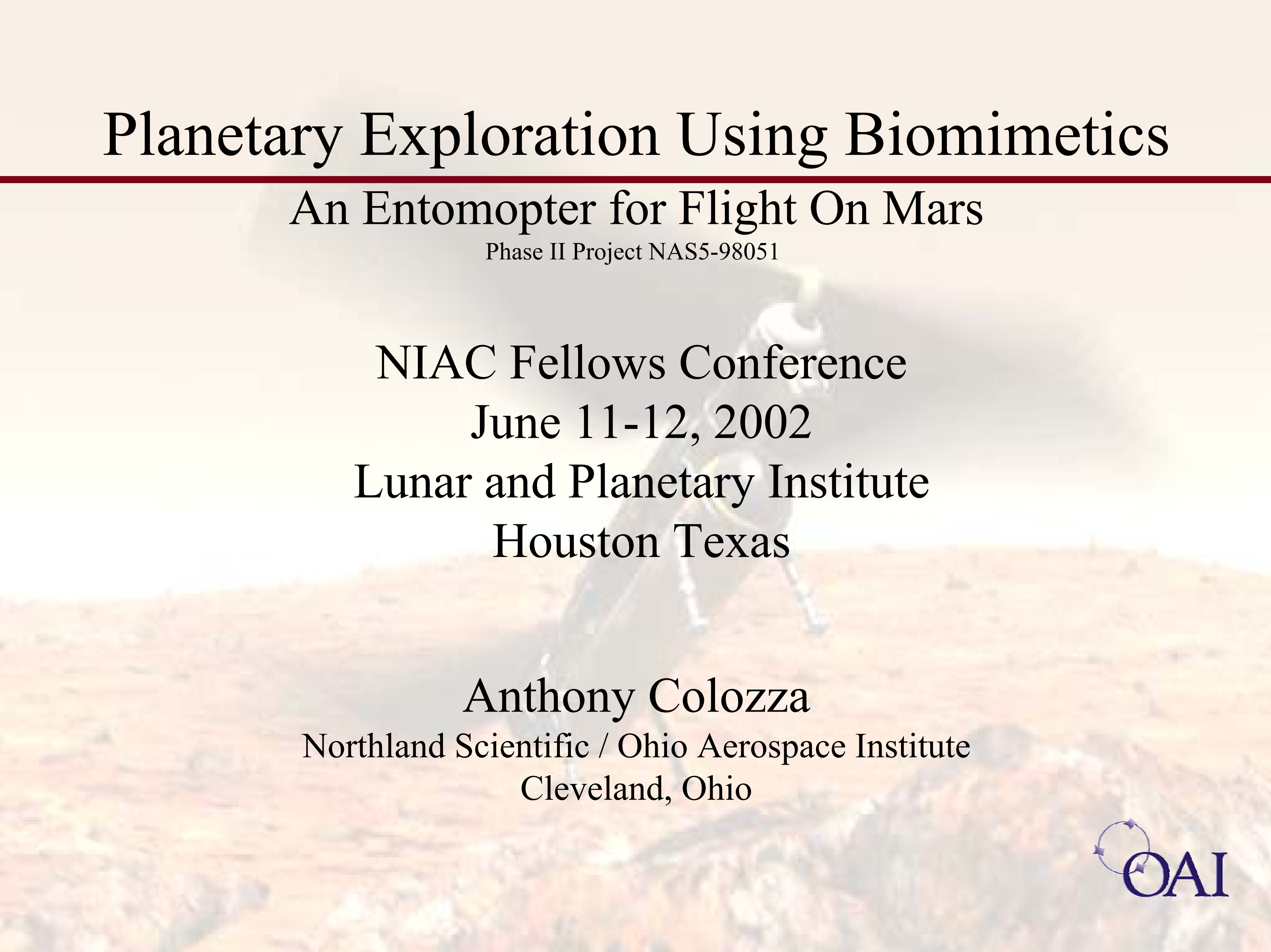


Planetary Exploration Using Biomimetics

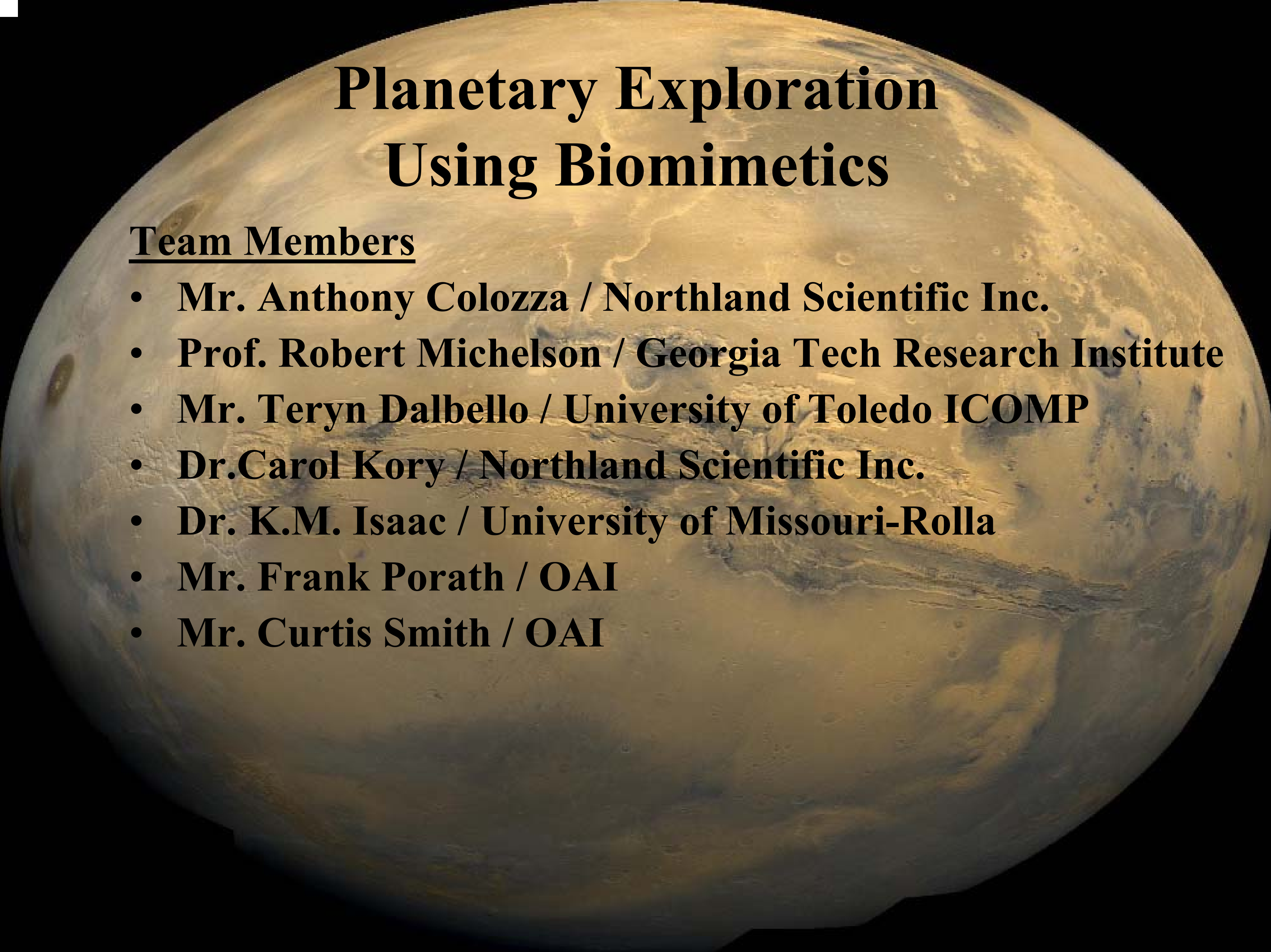
An Entomopter for Flight On Mars

Phase II Project NAS5-98051

NIAC Fellows Conference
June 11-12, 2002
Lunar and Planetary Institute
Houston Texas

Anthony Colozza
Northland Scientific / Ohio Aerospace Institute
Cleveland, Ohio

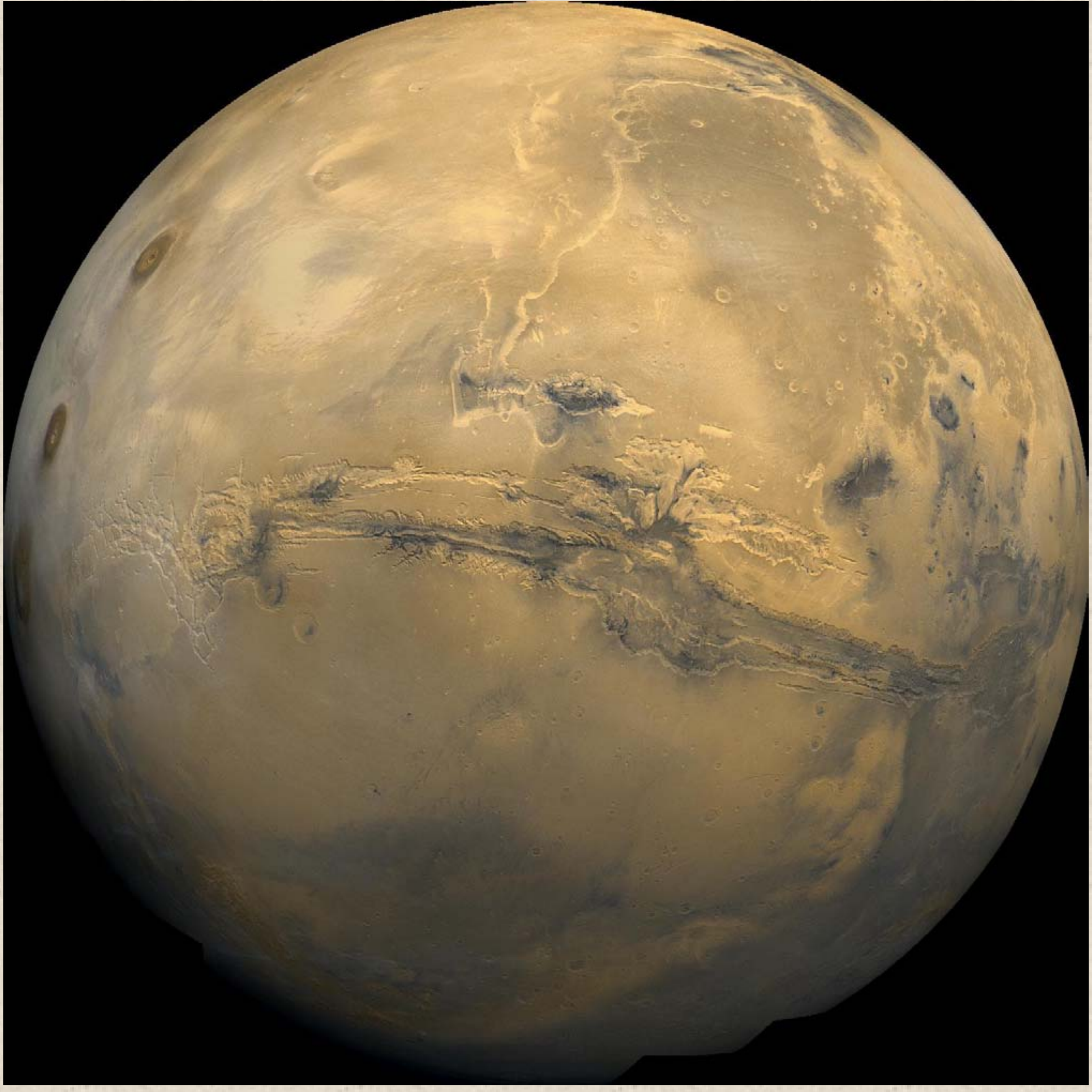
Planetary Exploration Using Biomimetics



Team Members

- Mr. Anthony Colozza / Northland Scientific Inc.
- Prof. Robert Michelson / Georgia Tech Research Institute
- Mr. Teryn Dalbello / University of Toledo ICOMP
- Dr.Carol Kory / Northland Scientific Inc.
- Dr. K.M. Isaac / University of Missouri-Rolla
- Mr. Frank Porath / OAI
- Mr. Curtis Smith / OAI

Mars Exploration

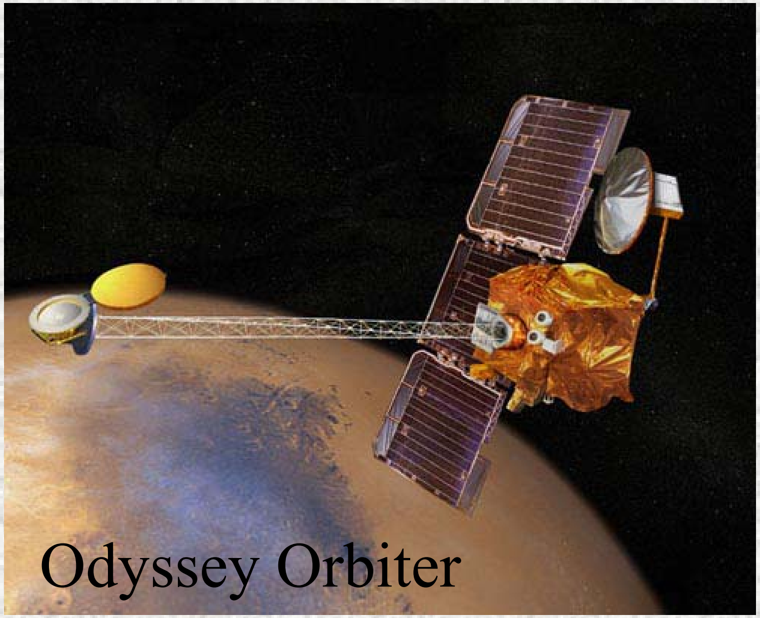


Mars has been the primary object of planetary exploration for the past 25 years

To date all exploration vehicles have been landers orbiters and a rover

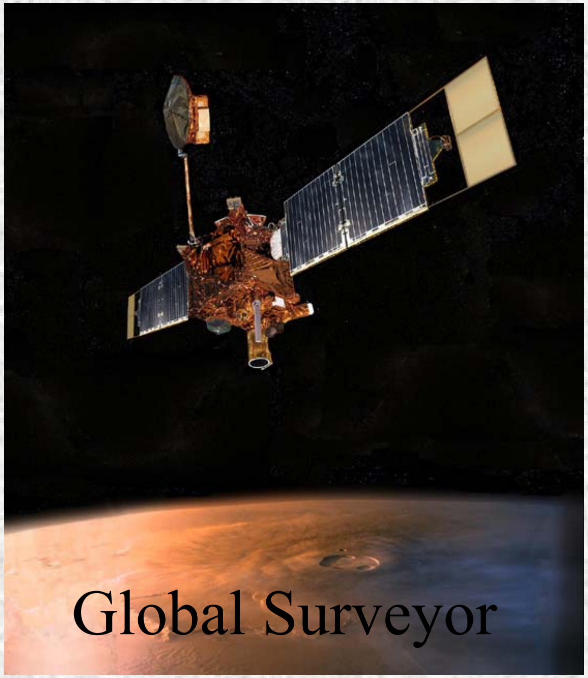
The next method of exploration that makes sense for mars is a flight vehicle

Mars Exploration

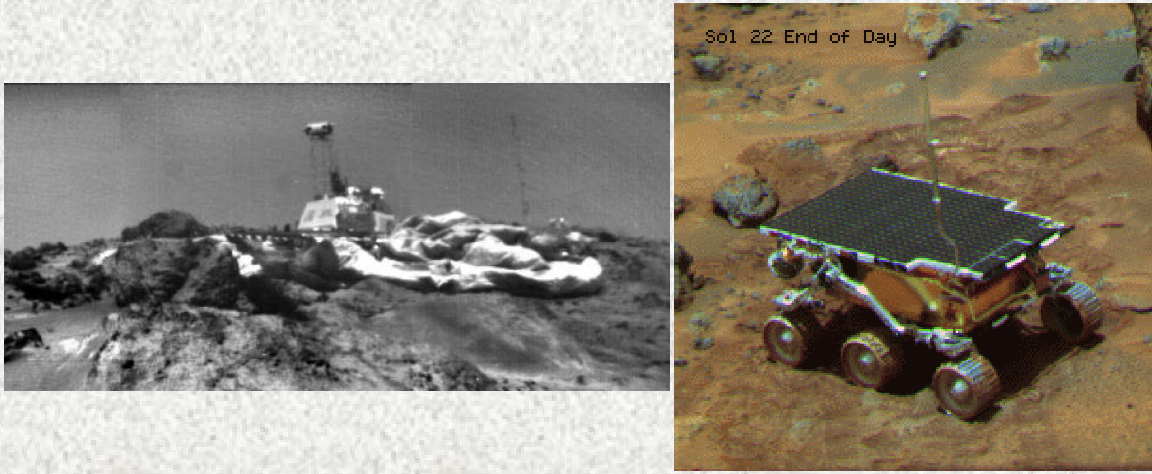


Odyssey Orbiter

Viking I & II
Lander & Orbiter

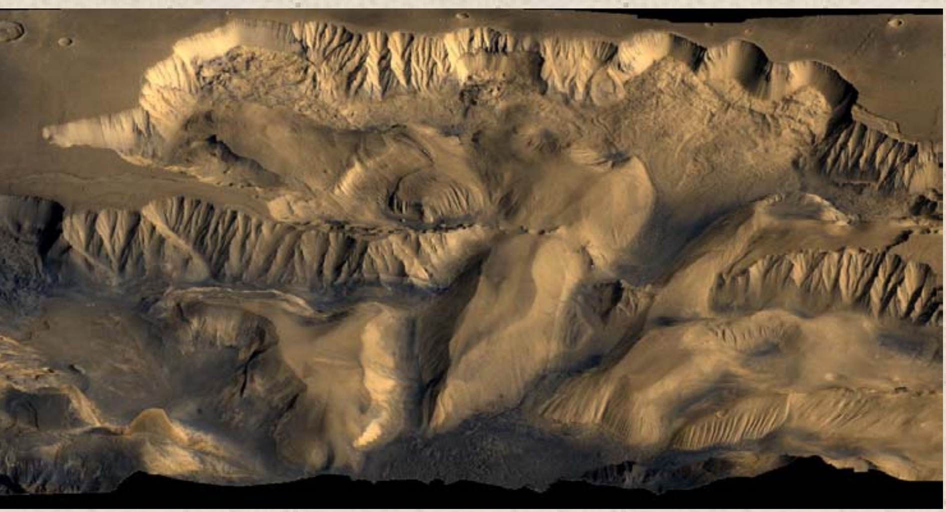


Global Surveyor

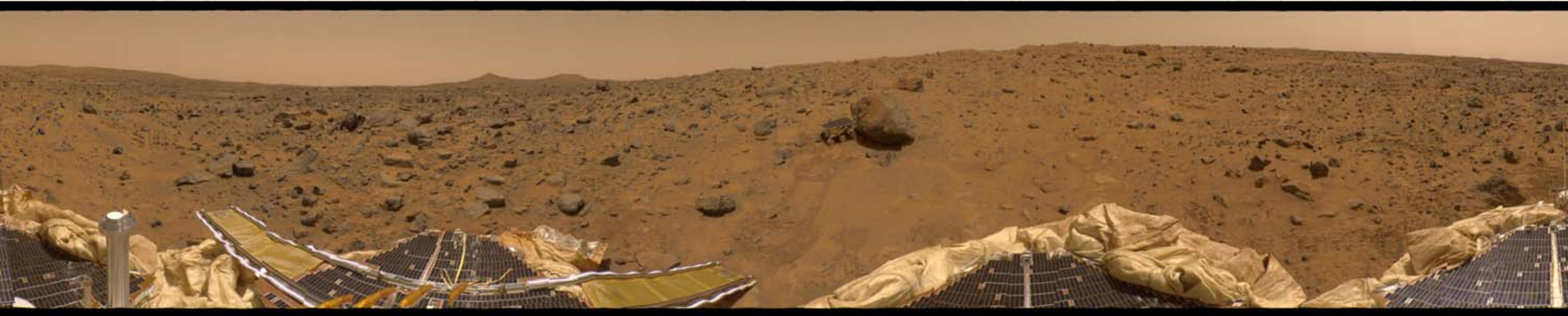


Pathfinder Lander & Rover

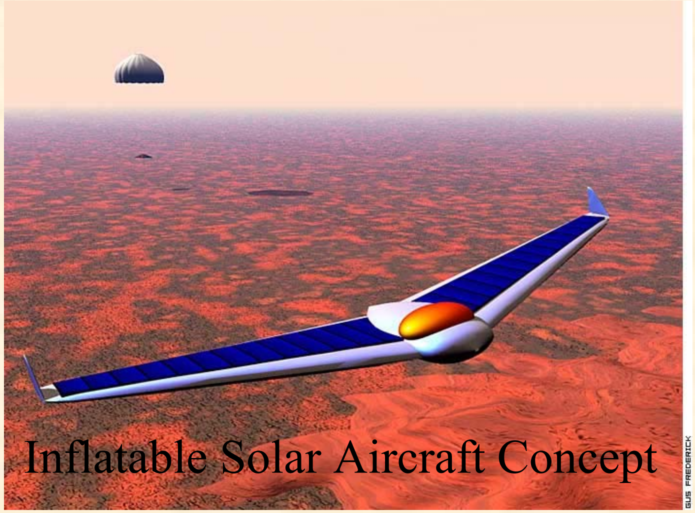
Mars Environment



	Mars	Earth
Temp Range & Mean	-143°C to 27°C -43°C	-62°C to 50°C 15°C
Surface Pressure	650 Pa	103300 Pa
Gravity	3.75 m/s^2	9.81 m/s^2
Day Length	24.6 hrs	23.94 hrs
Year Length	686 days	365.26 days
Diameter	6794 km	12756 km
Atmosphere Composition	CO_2	N_2, O_2



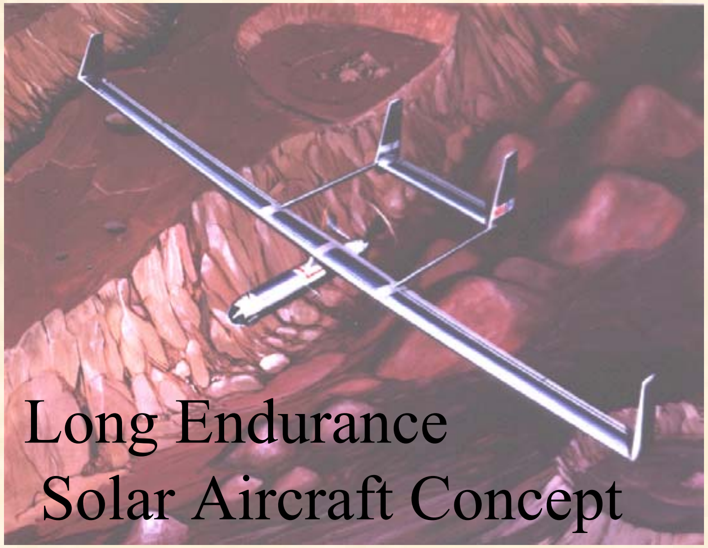
History of Mars Aircraft Concepts



Inflatable Solar Aircraft Concept

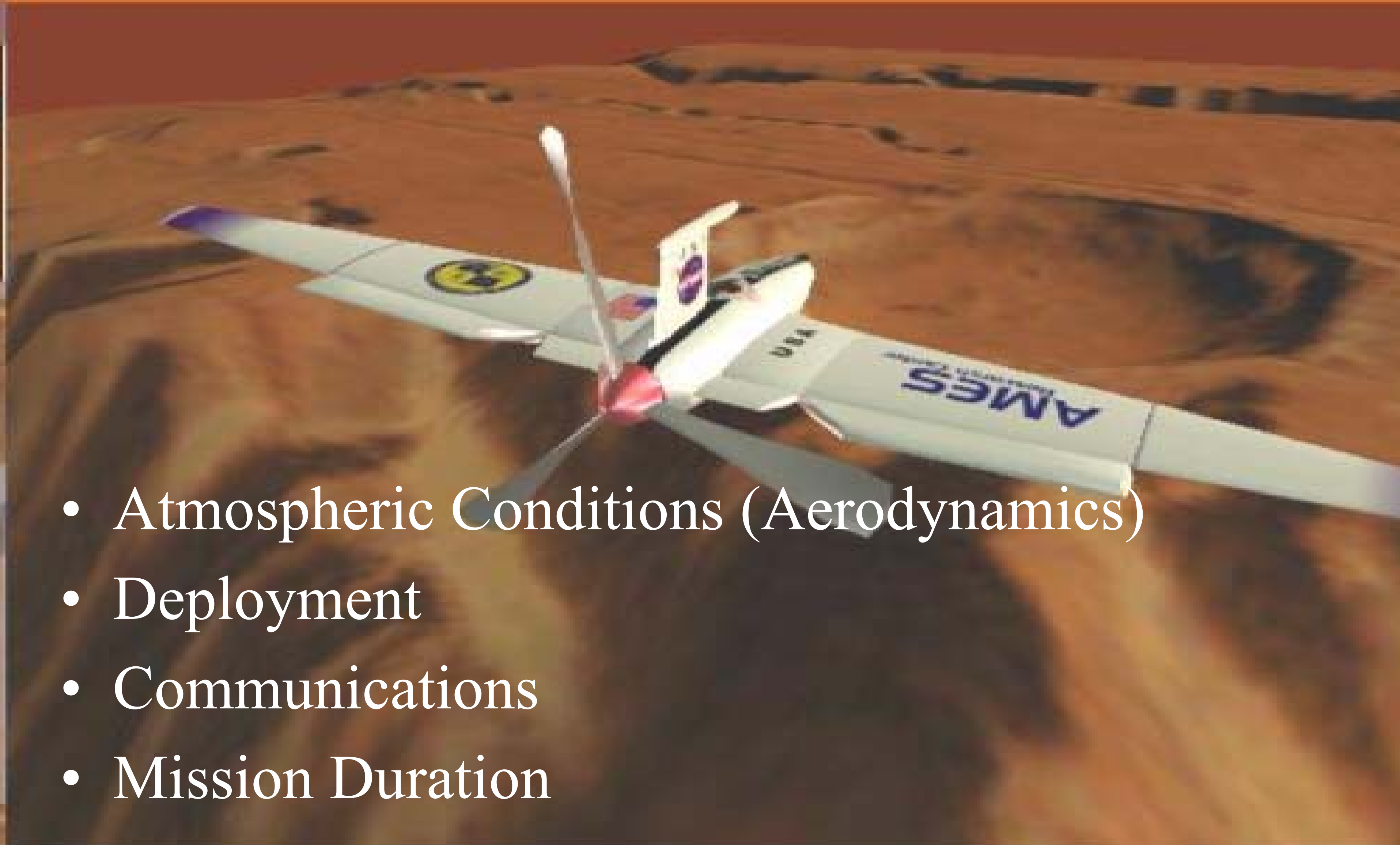
Hydrazine Power Aircraft Concept

MiniSniffer Aircraft



Long Endurance Solar Aircraft Concept

Key Challenges to Flight On Mars



- Atmospheric Conditions (Aerodynamics)
- Deployment
- Communications
- Mission Duration

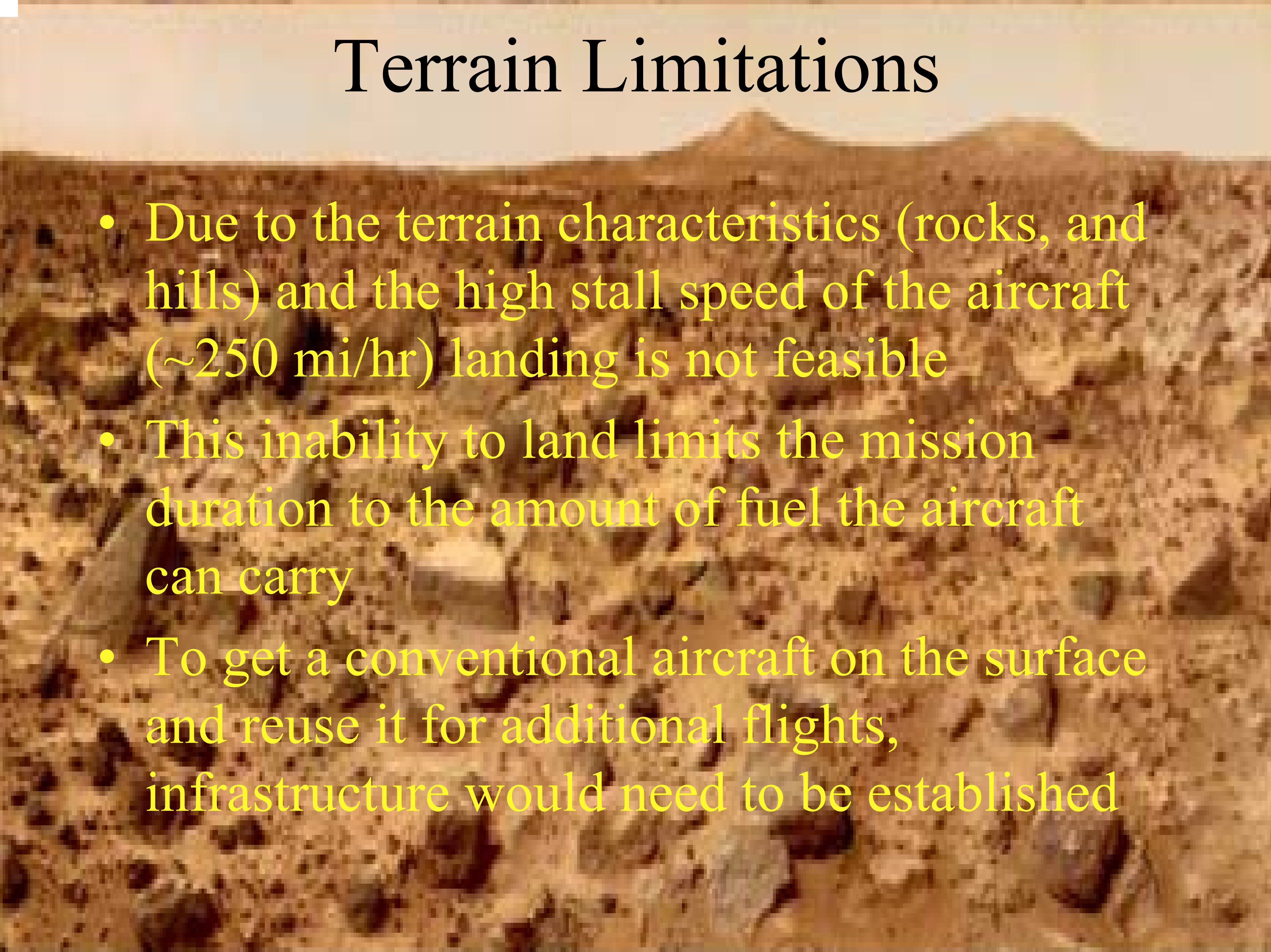
Environment: Atmosphere

- Very low atmospheric density near the surface of Mars (1/70th that of the Earths surface)
  - This is similar to flying at around 30 km (110 kft) on Earth
- 22% Lower speed of sound then on Earth
  - Due to CO_2 Atmosphere
  - Limits speed of aircraft and propeller
- High stall speed requires aircraft to fly fast to maintain lift
- Requires flight in a low Reynolds number high Mach number flight regime

$$Re = \frac{\rho V L}{\mu} \qquad M = \frac{V}{a}$$

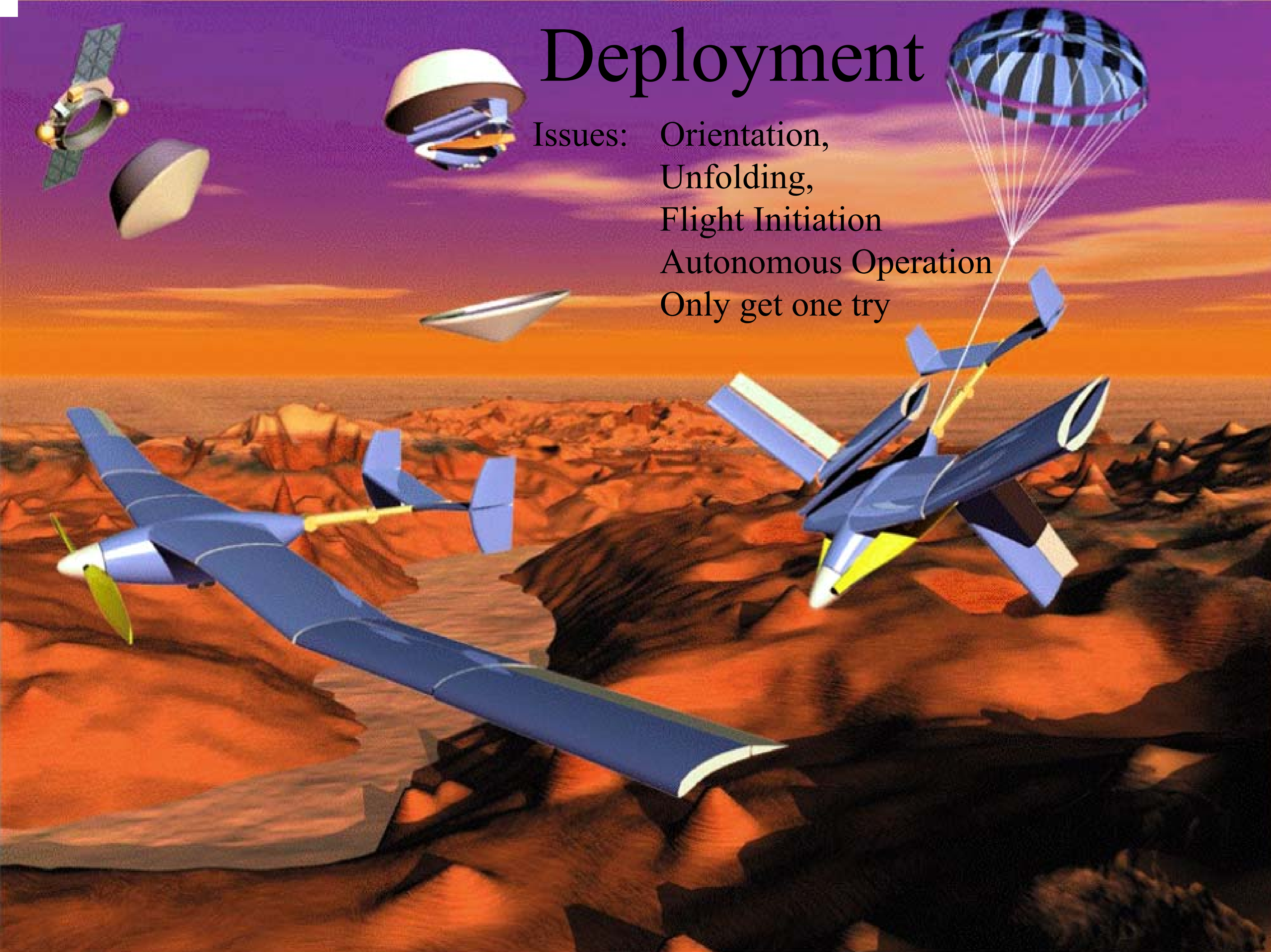
- Flow separation causes aircraft to stall abruptly

Terrain Limitations



- Due to the terrain characteristics (rocks, and hills) and the high stall speed of the aircraft (~250 mi/hr) landing is not feasible
- This inability to land limits the mission duration to the amount of fuel the aircraft can carry
- To get a conventional aircraft on the surface and reuse it for additional flights, infrastructure would need to be established

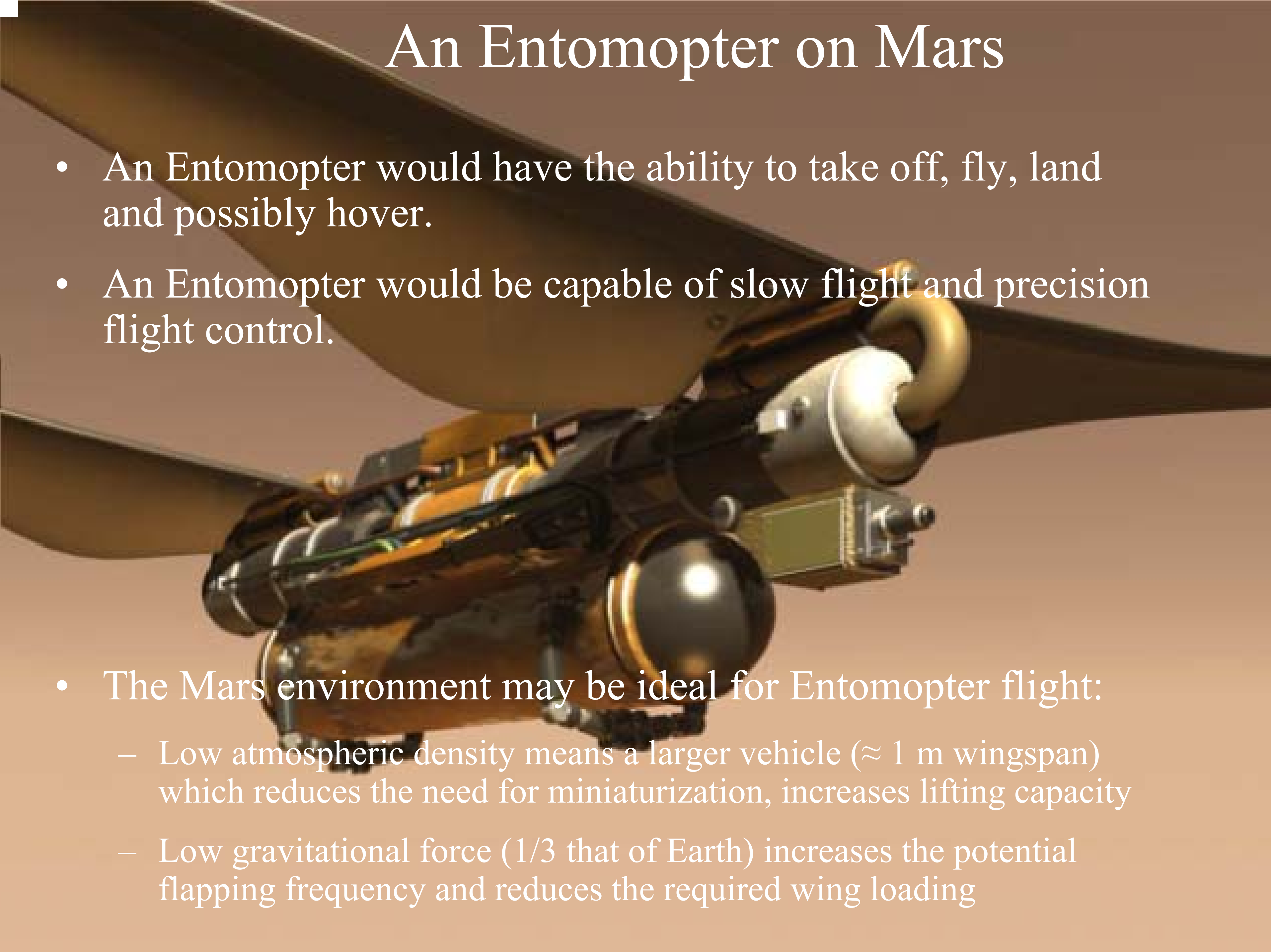
Deployment



Issues: Orientation,
Unfolding,
Flight Initiation
Autonomous Operation
Only get one try

Communications Link

- Communications time is limited by the flight duration, which in turn is set by the amount of fuel the aircraft can carry
- This presents a problem when trying to relay large amounts of data over a relatively short time period (30 min to a few hours)
  - This compares to other missions (pathfinder) which have months to relay data
- The logistics and timing of coordinating the aircraft flight path and the availability of a satellite communications link are difficult

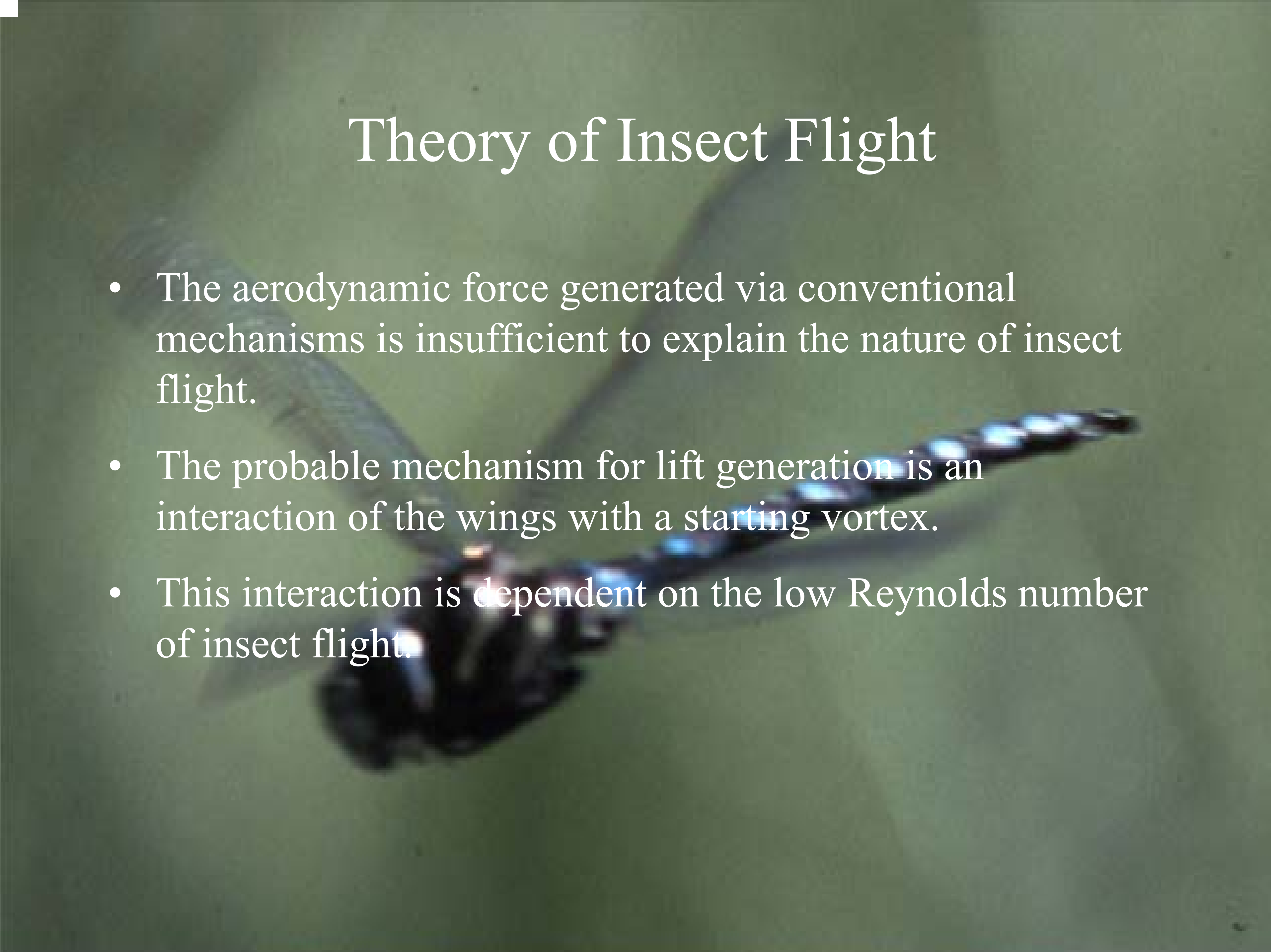


An Entomopter on Mars

- An Entomopter would have the ability to take off, fly, land and possibly hover.
- An Entomopter would be capable of slow flight and precision flight control.
- The Mars environment may be ideal for Entomopter flight:
  - Low atmospheric density means a larger vehicle (≈ 1 m wingspan) which reduces the need for miniaturization, increases lifting capacity
  - Low gravitational force (1/3 that of Earth) increases the potential flapping frequency and reduces the required wing loading

Project Goal

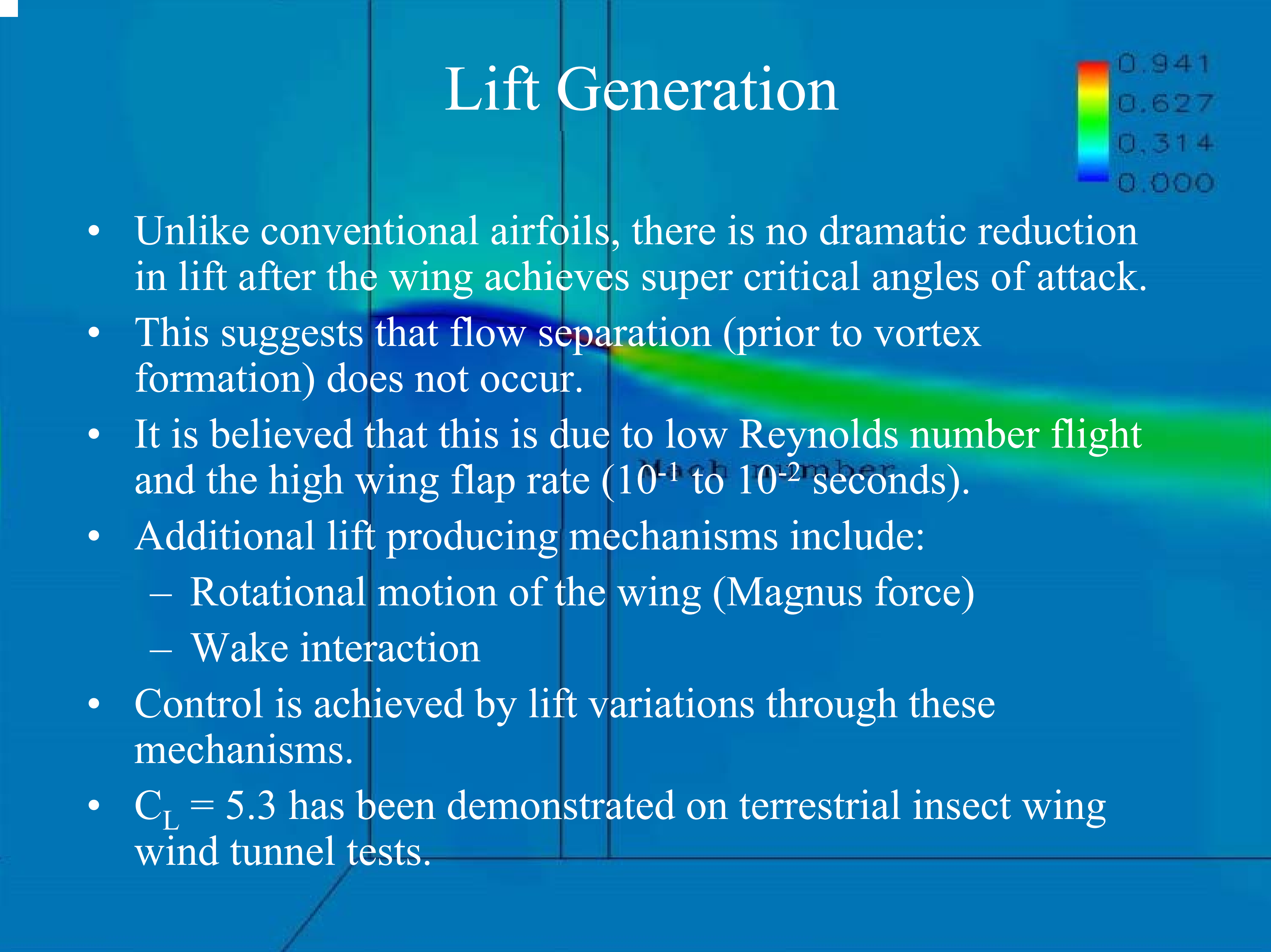
The Goal of this Project is to Use the Present State of Knowledge on Entomopter Development and Apply this to Developing an Entomopter for the Mars Environment.



Theory of Insect Flight

- The aerodynamic force generated via conventional mechanisms is insufficient to explain the nature of insect flight.
- The probable mechanism for lift generation is an interaction of the wings with a starting vortex.
- This interaction is dependent on the low Reynolds number of insect flight.

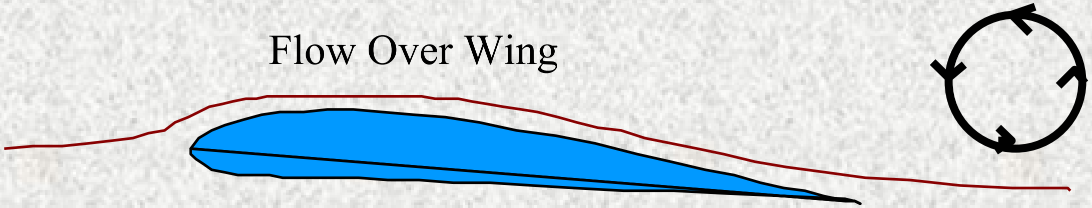
Lift Generation



- Unlike conventional airfoils, there is no dramatic reduction in lift after the wing achieves super critical angles of attack.
- This suggests that flow separation (prior to vortex formation) does not occur.
- It is believed that this is due to low Reynolds number flight and the high wing flap rate (10^{-1} to 10^{-2} seconds).
- Additional lift producing mechanisms include:
  - Rotational motion of the wing (Magnus force)
  - Wake interaction
- Control is achieved by lift variations through these mechanisms.
- $C_L = 5.3$ has been demonstrated on terrestrial insect wing wind tunnel tests.

The Main Difference Between Flapping Flight and Airfoil Flight is the Continual Formation and Shedding of the Wing Vortex in Flapping Flight.

Air Moves Over Wing Surface with no Separation.

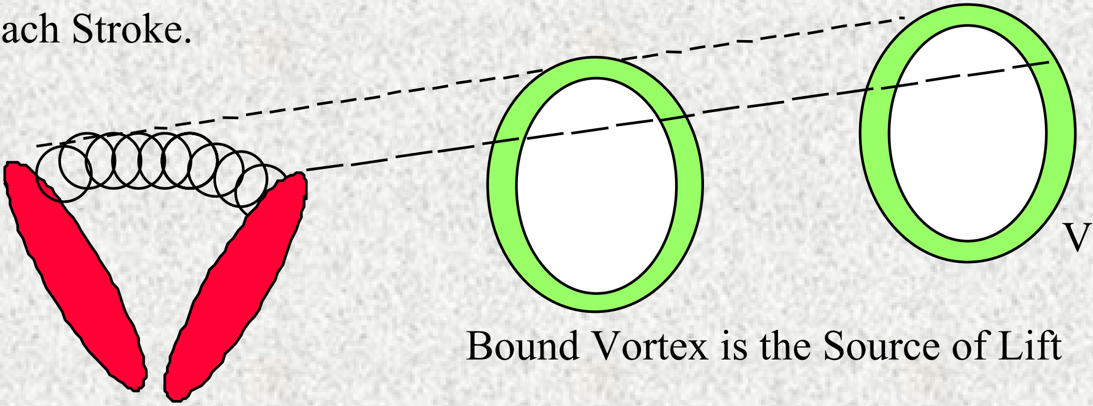


Flow Over Wing

Trailing Vortex

Vortex Does Not
Affect Lift Generation
by the Wing.

Conventional Airfoil Produces a Steady State Standing Vortex.



Bound Vortex is Formed
After Each Stroke.

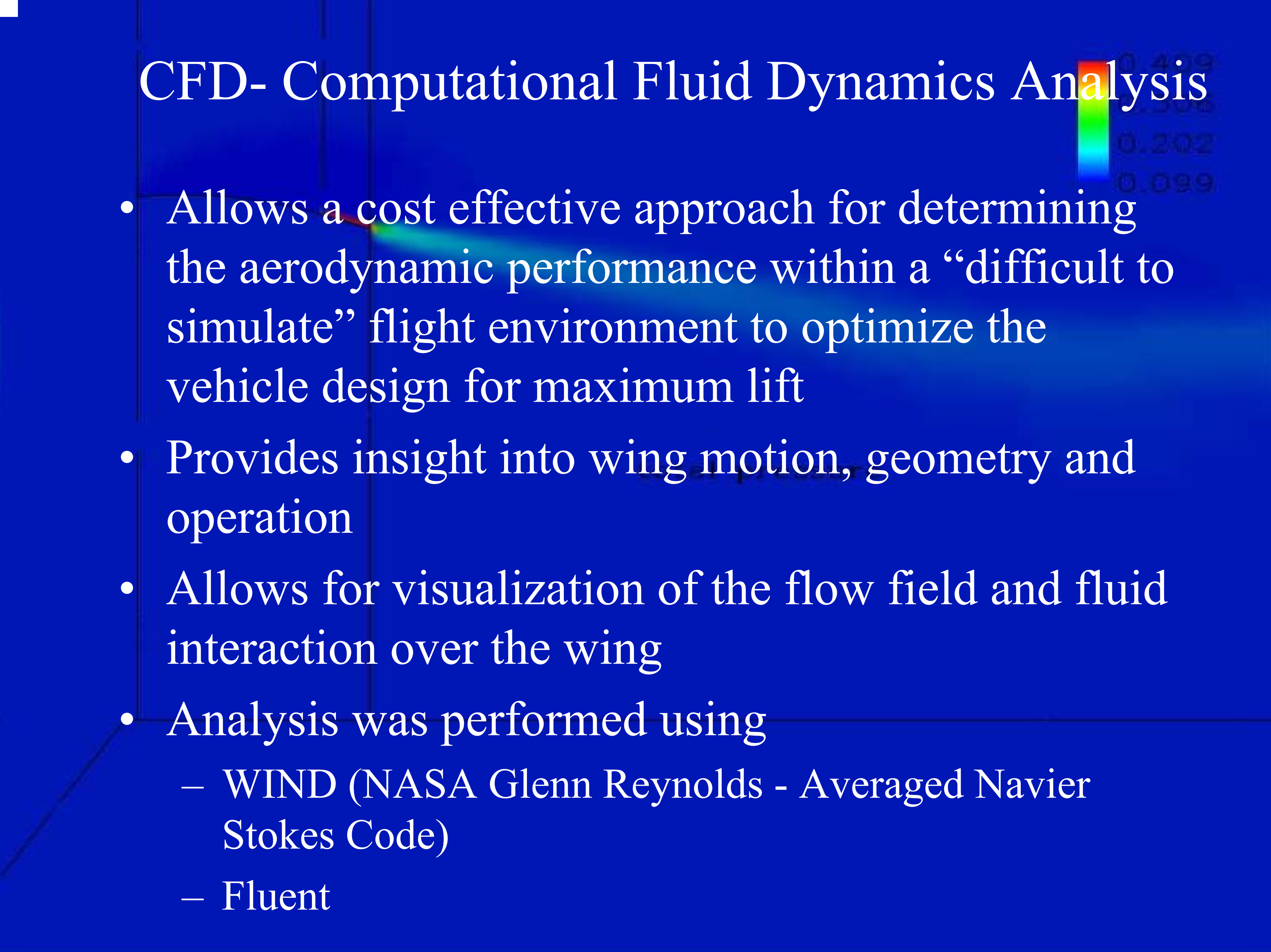
Vortex is Shed After
each Stroke

3 Dimensional
Wake Structure

Vortex Tube

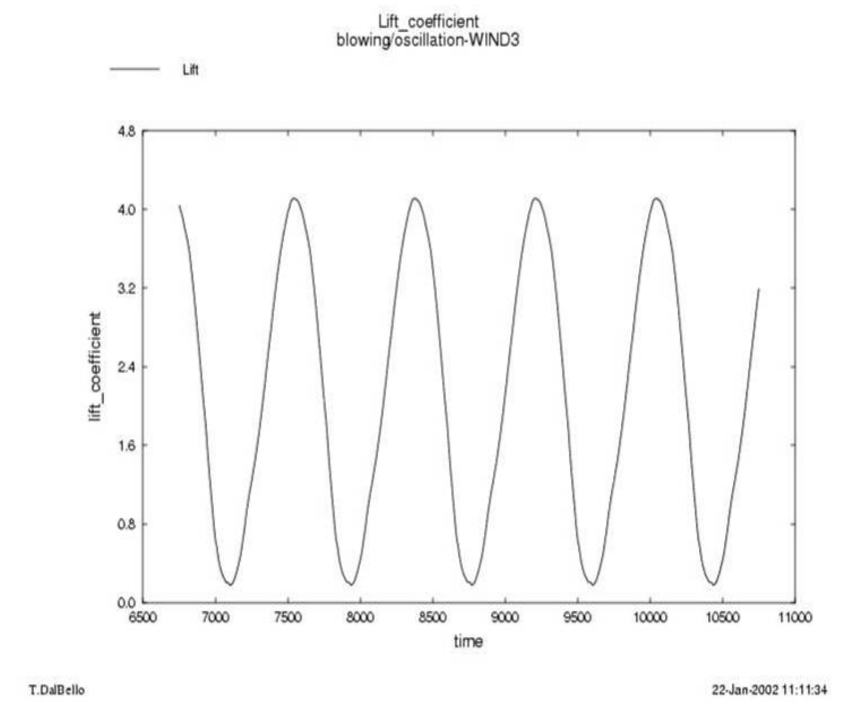
Bound Vortex is the Source of Lift

CFD- Computational Fluid Dynamics Analysis

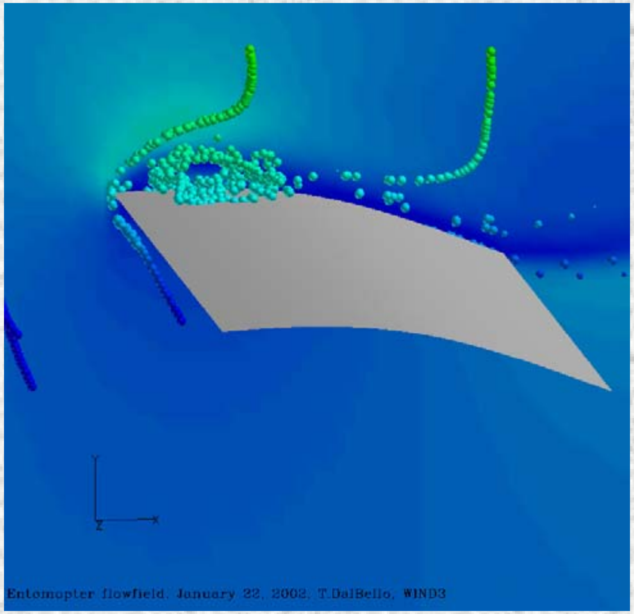


- Allows a cost effective approach for determining the aerodynamic performance within a “difficult to simulate” flight environment to optimize the vehicle design for maximum lift
- Provides insight into wing motion, geometry and operation
- Allows for visualization of the flow field and fluid interaction over the wing
- Analysis was performed using
  - WIND (NASA Glenn Reynolds - Averaged Navier Stokes Code)
  - Fluent

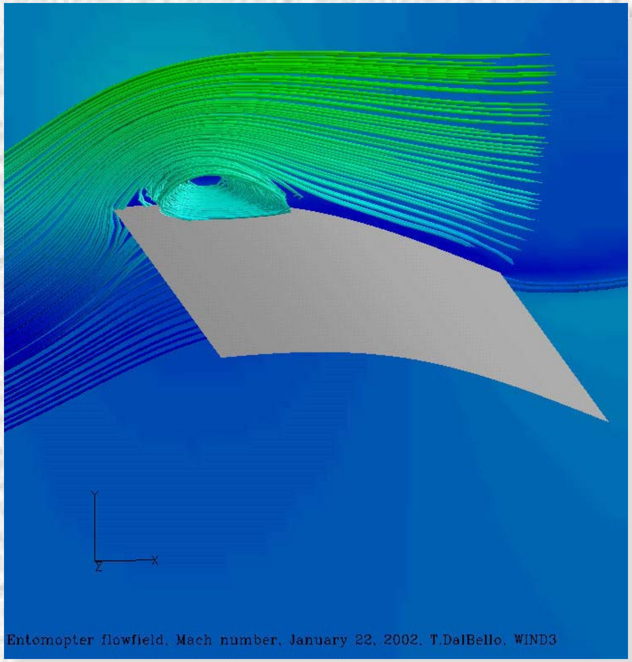
WIND CFD Analysis Progress



Oscillating Lift Coefficient



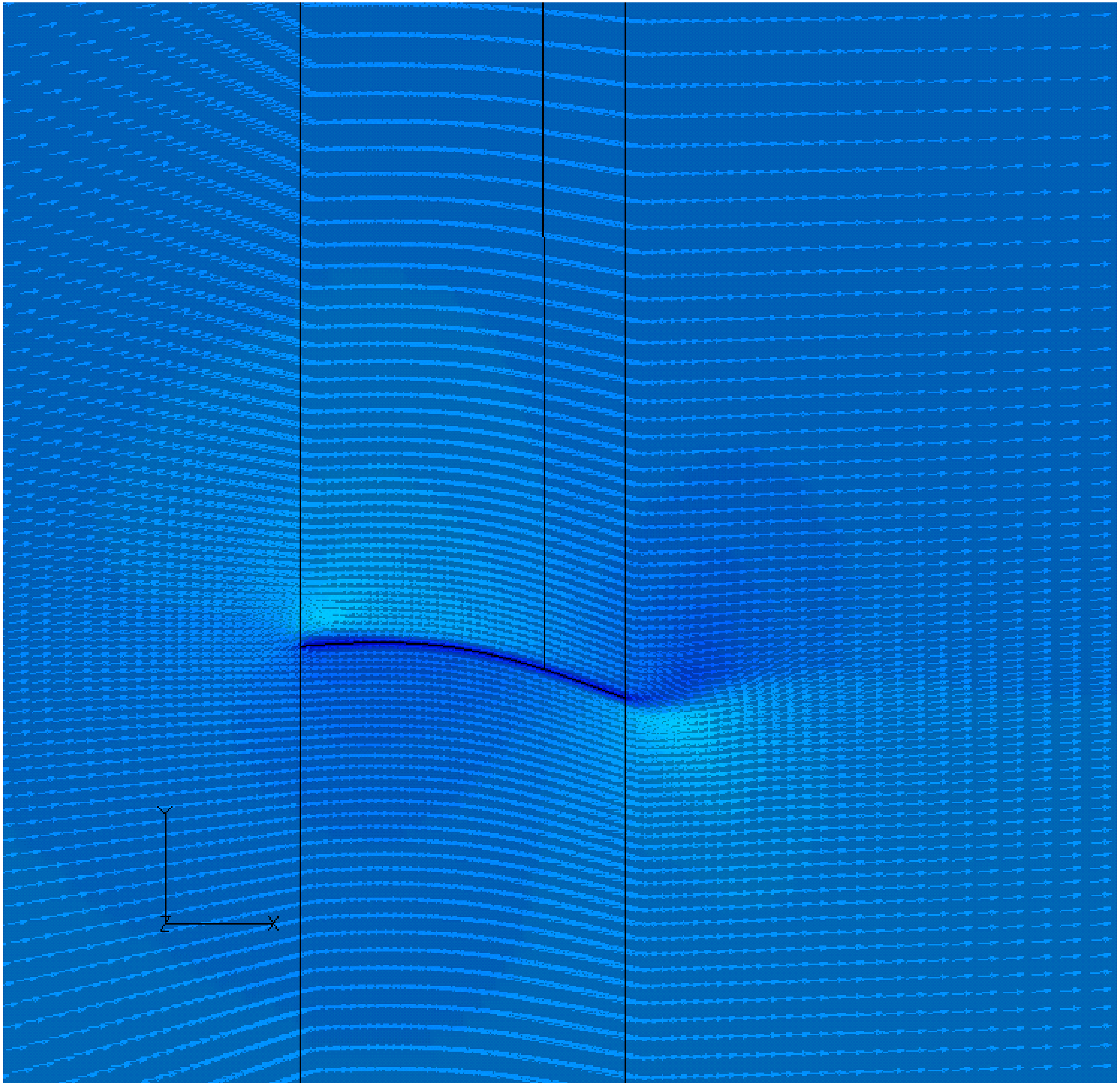
Entomopter flowfield, January 22, 2002, T.DalBello, WIND3



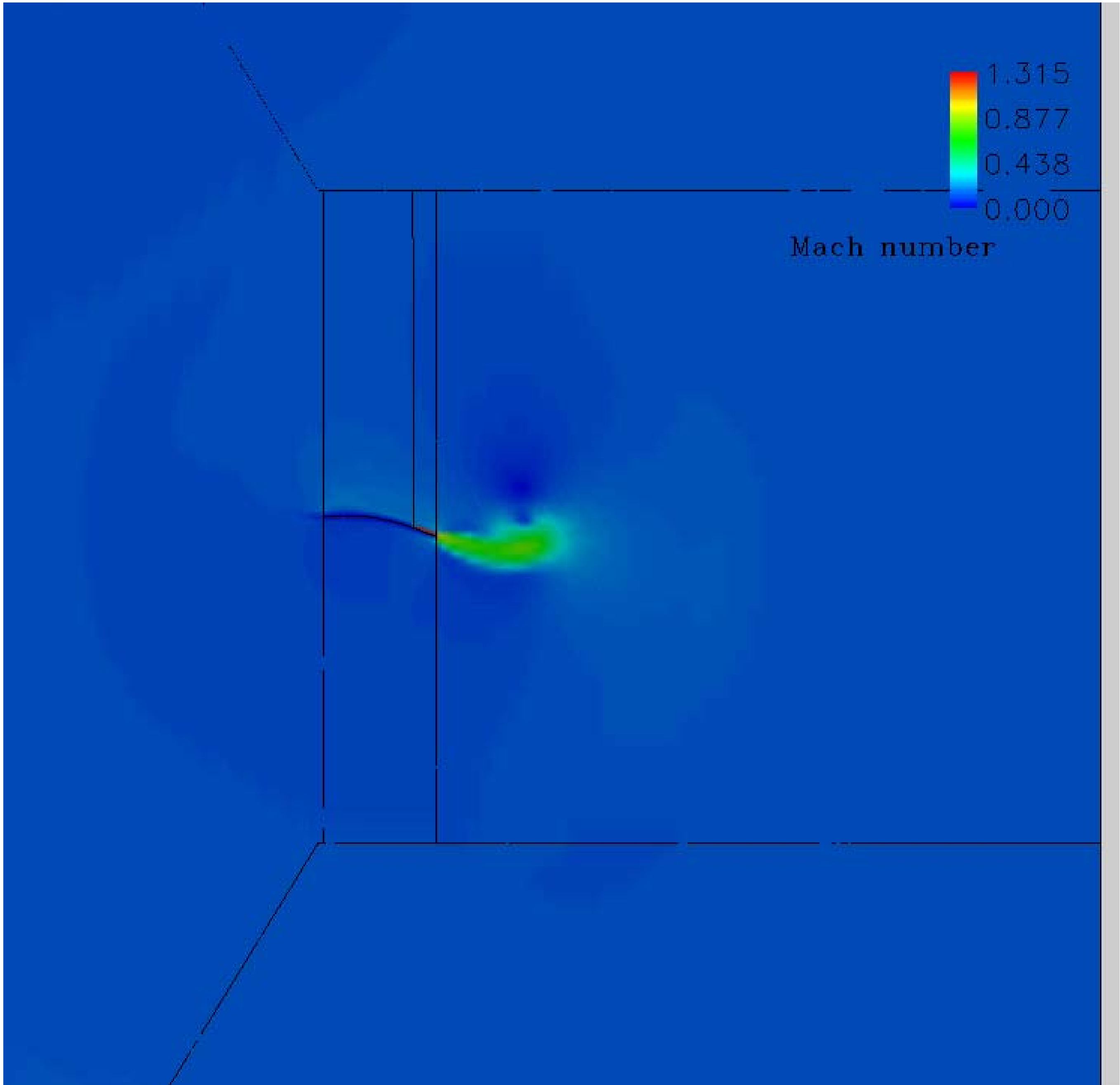
Entomopter flowfield, Mach number, January 22, 2002, T.DalBello, WIND3

No Blowing
5° Angle of Attack
Maximum Cl ~4.0
Cd varies between ~0.2 to ~0.8
Cambered Airfoil with Zero Thickness
Grid had 8 Zones ~ 500,000 pts

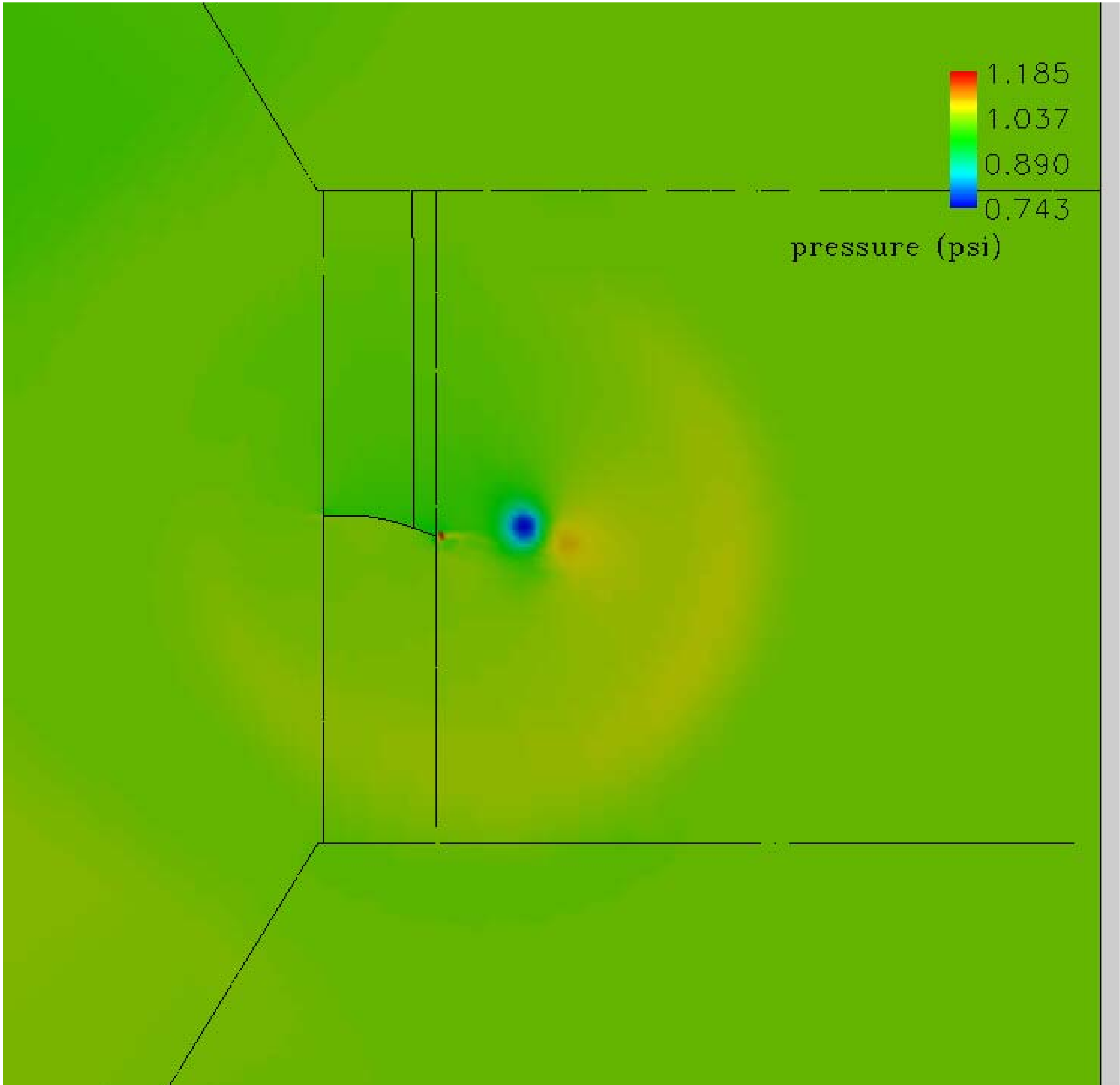
Vortex Formation (WIND Simulation)



Mach Number (Wind Simulation)



Pressure Contours (WIND Simulation)



FLUENT Analysis Progress

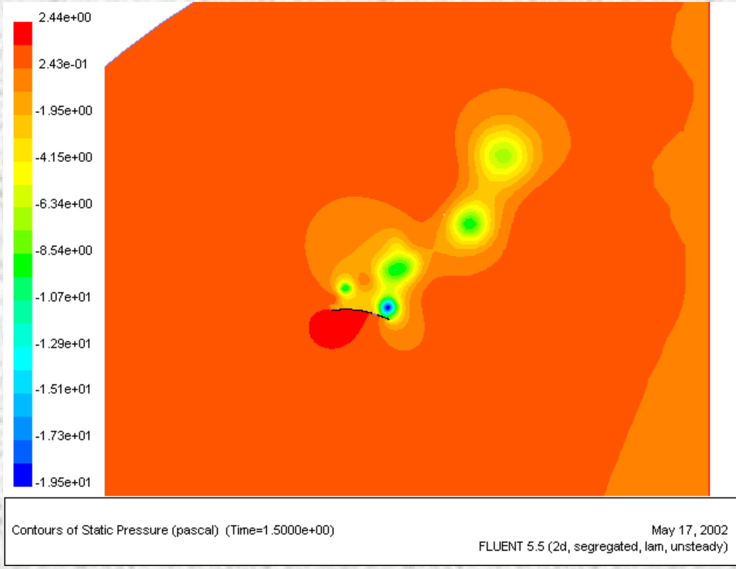
Demonstrated that a vortex formed at the leading edge will stay attached to the top surface, grow, and convect downstream

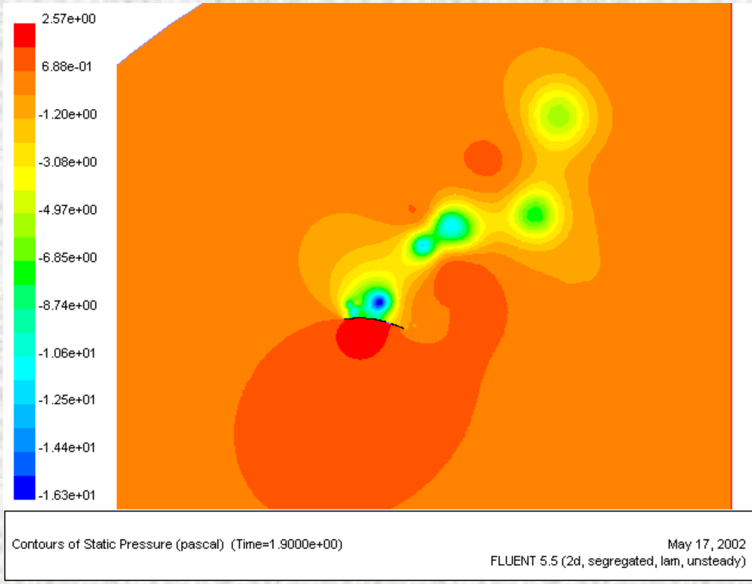
Leading edge vortex has a strong Reynolds number dependency

Lift can be further augmented by optimizing operational Reynolds number and wing kinematics

No active blowing was utilized

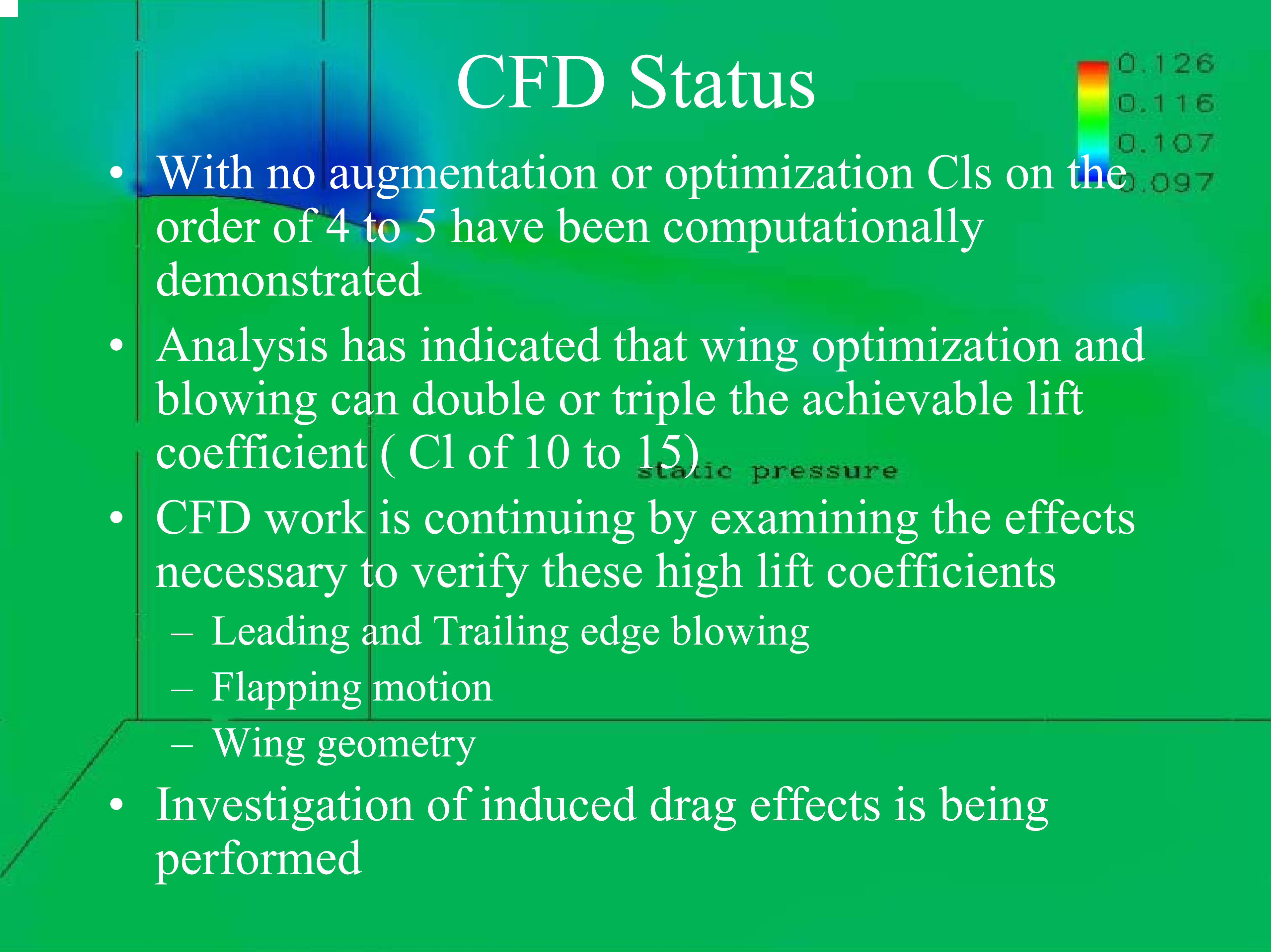
Maximum lift coefficient of 4.27 was realized





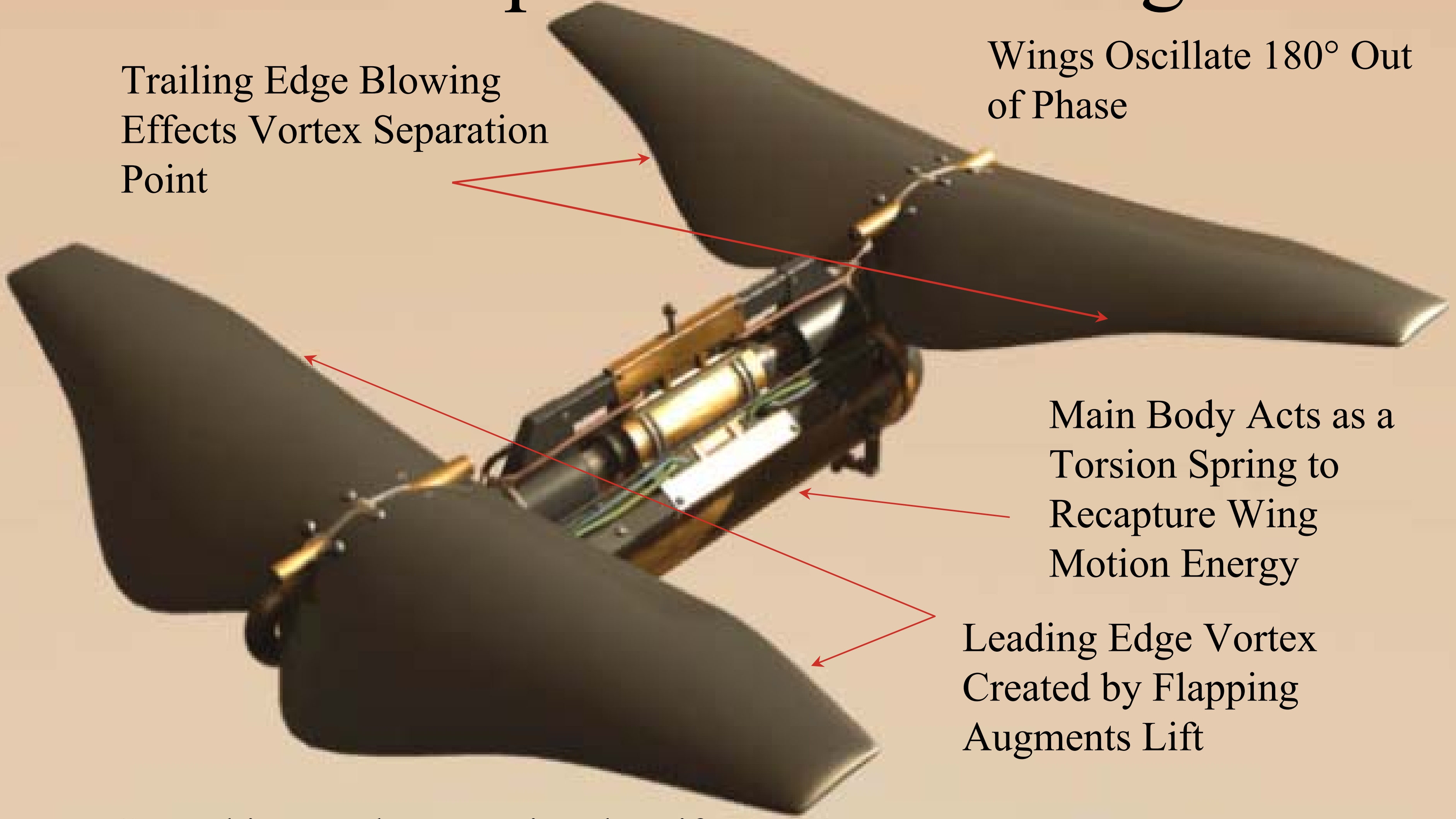
Pressure $\alpha = 46$, Re = 5100

CFD Status



- With no augmentation or optimization Cls on the order of 4 to 5 have been computationally demonstrated
- Analysis has indicated that wing optimization and blowing can double or triple the achievable lift coefficient (Cl of 10 to 15)
- CFD work is continuing by examining the effects necessary to verify these high lift coefficients
  - Leading and Trailing edge blowing
  - Flapping motion
  - Wing geometry
- Investigation of induced drag effects is being performed

Entomopter Vehicle Design



Trailing Edge Blowing Effects Vortex Separation Point

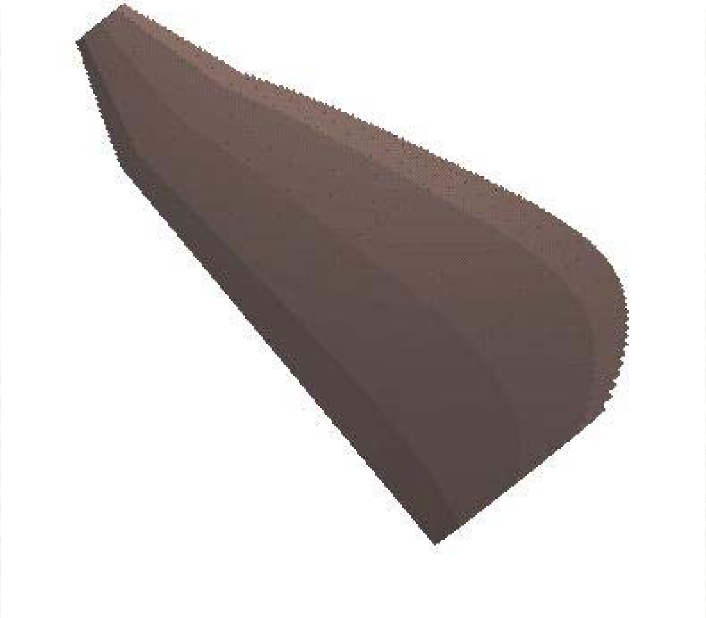
Wings Oscillate 180° Out of Phase

Main Body Acts as a Torsion Spring to Recapture Wing Motion Energy

Leading Edge Vortex Created by Flapping Augments Lift

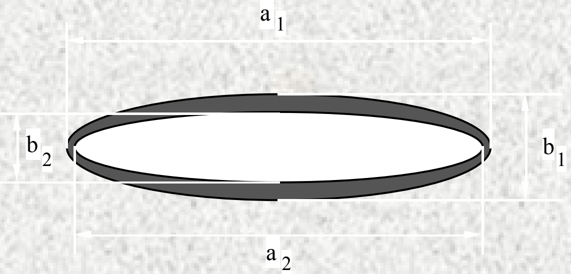
Control is Based on Varying the Lift on each Wing by Controlling Vortex Formation Through Boundary Layer Blowing

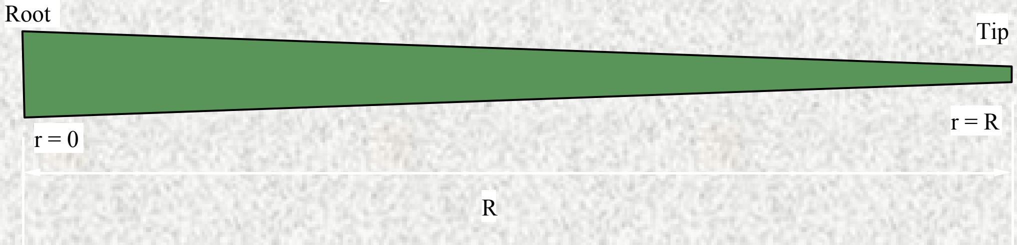
Wing Layout and Structure



Elliptical Core enables more mass to be distributed to the upper
And lower surfaces and less to the leading and trailing edges

Taper ratio is linear from the root to tip

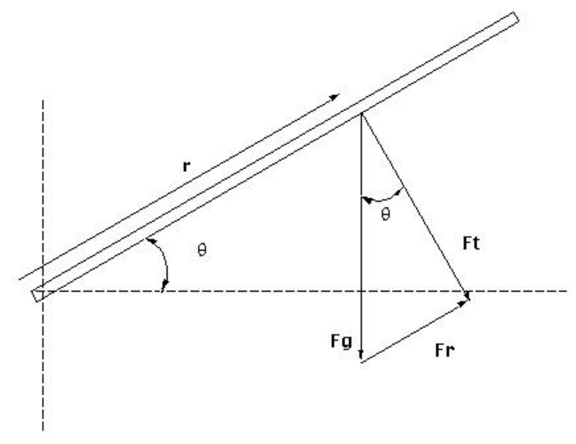


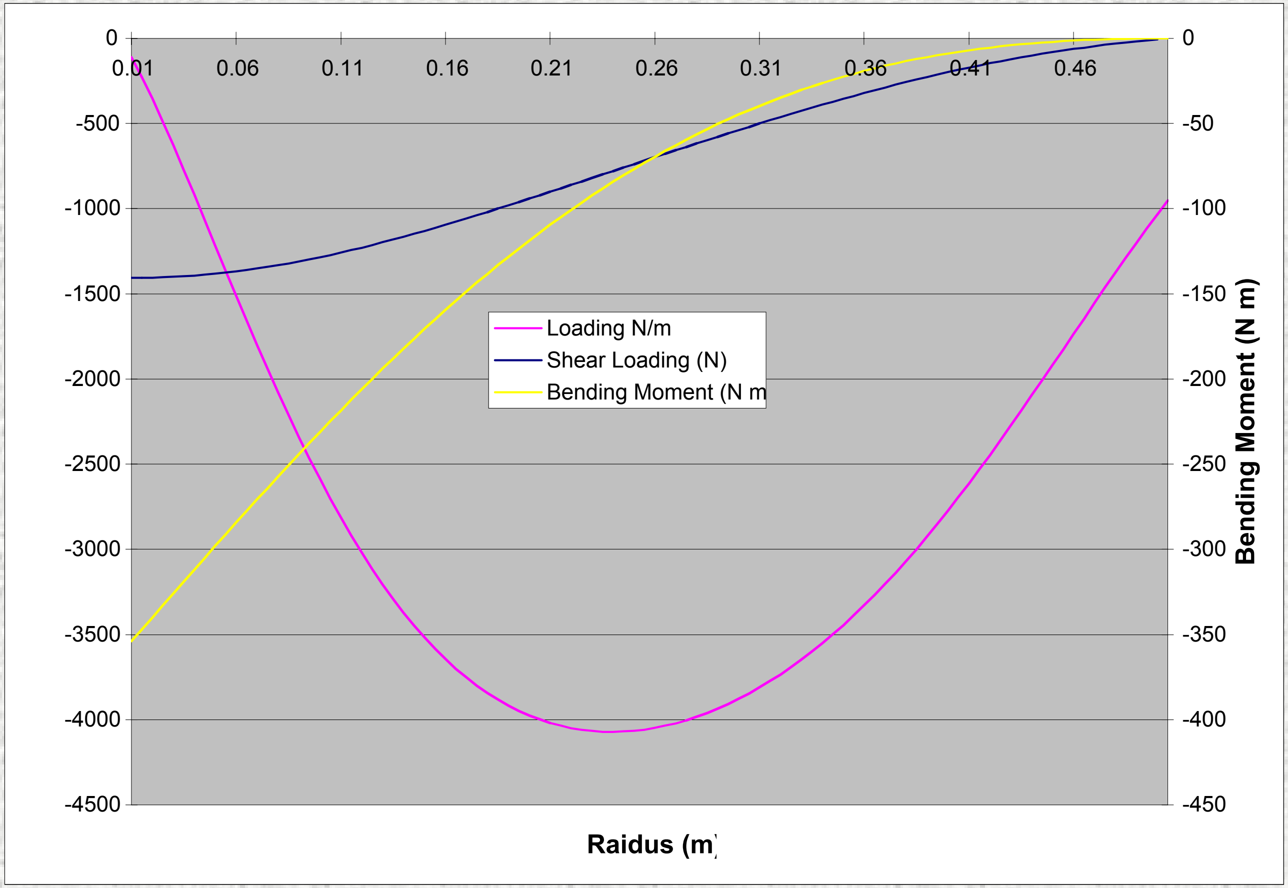


Wing, Bending and Shear Loads

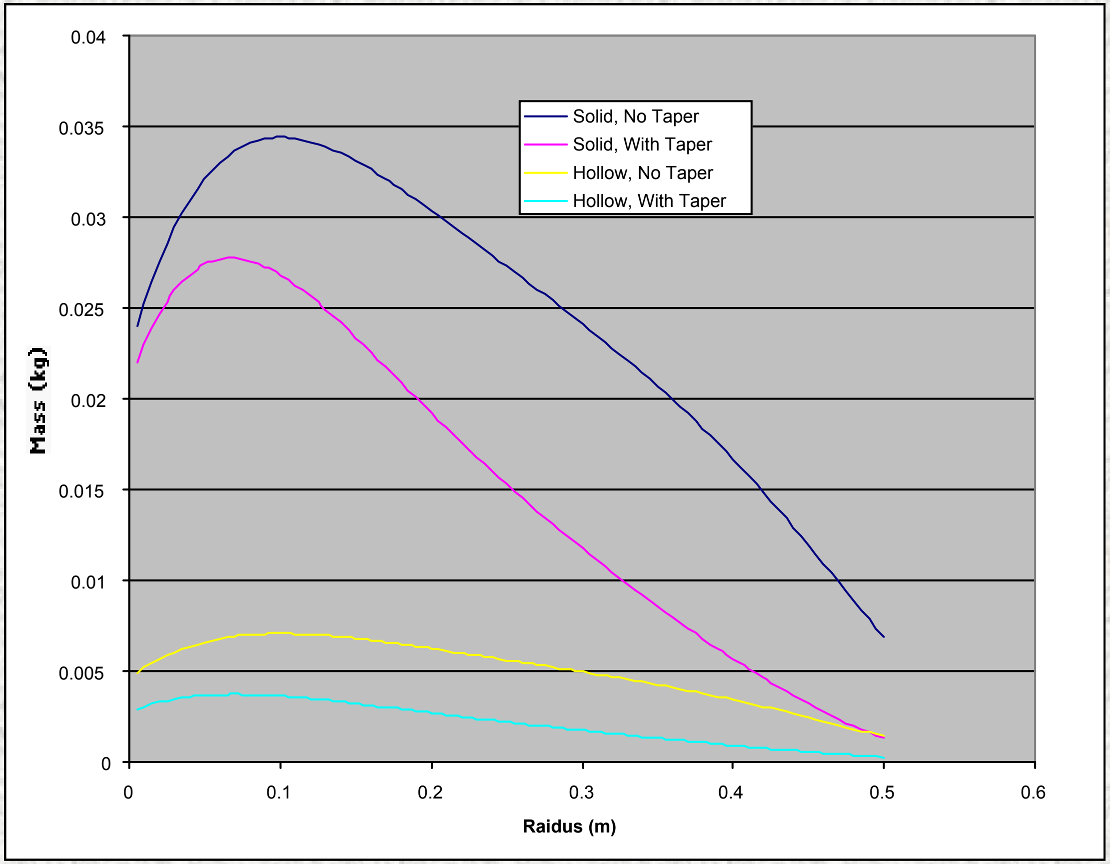
For hollow tapered wing section

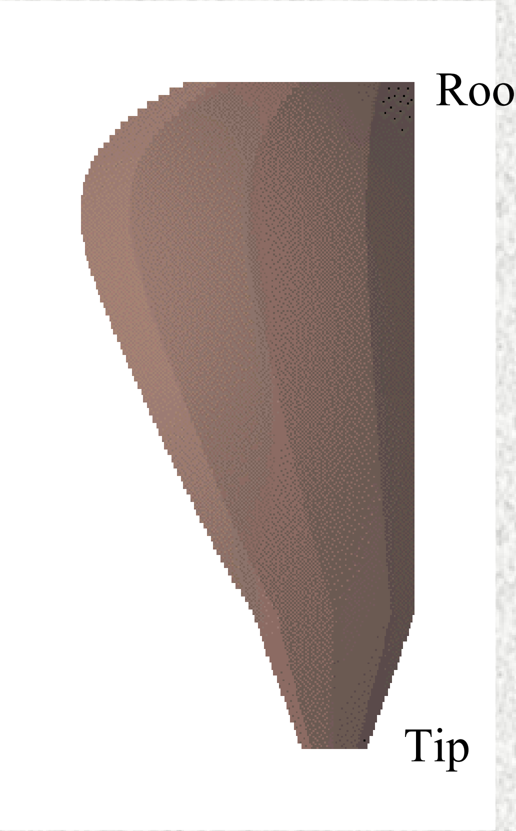
Main forces: Gravity and acceleration /deceleration loads due to motion





Mass Distribution for Various Geometry Configurations

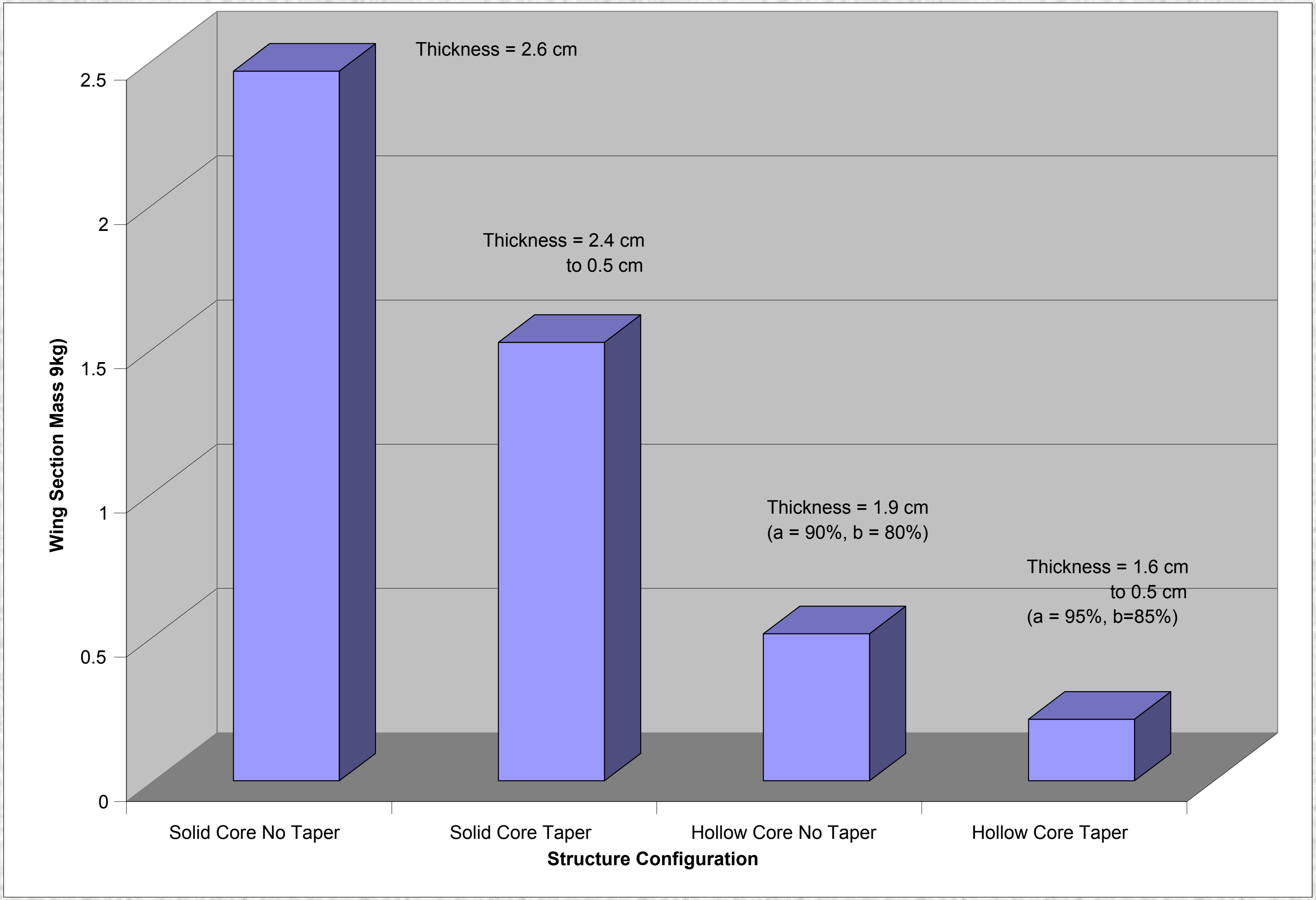




Wing Top View

Wing Section Mass Results

For a maximum tip deflection of 1.5 cm



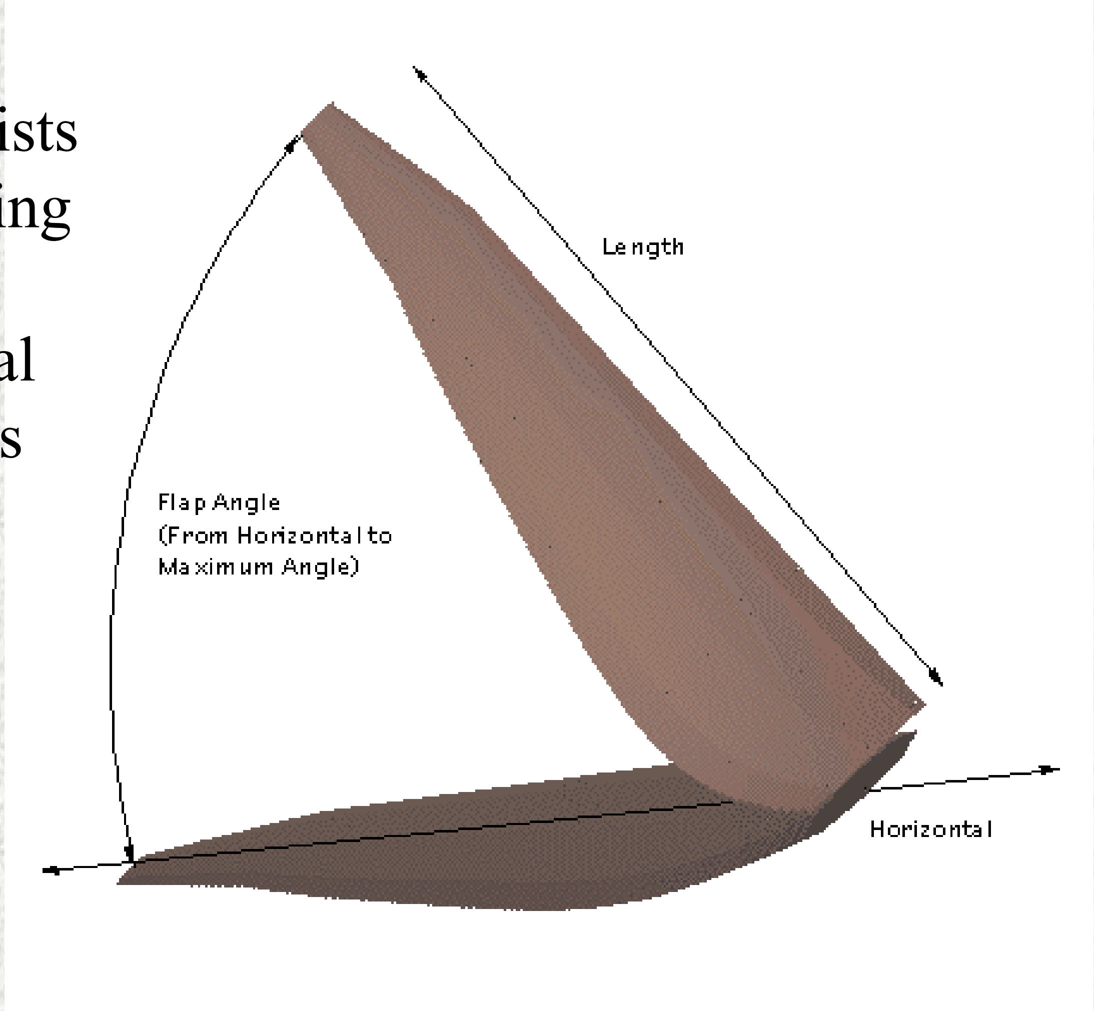
Entomopter Sizing and Power Requirements

- The energy required to move the wing and the lift generated by the wing are based on the wing geometry, mass distribution and operational conditions.
- Torsion Body Energy Capture was Not Included in the optimization
- An analysis and optimization was preformed to determine the baseline (or design point) configuration for the Mars environment
- Analysis variables and their ranges

Parameter	***Range***
Flight Velocity	2 to 30 m/s
Flapping Frequency	1 to 30 Hz
Wing Length	0.3 to 1.0 m
Flapping Angle	35° to 85°
Relative Lifting Capacity	0.5 to 2.0 kg

Wing Motion and Length

The motion of the wing consists of the maximum angle the wing segment moves upward or downward from the horizontal and the rate at which it moves through this angle

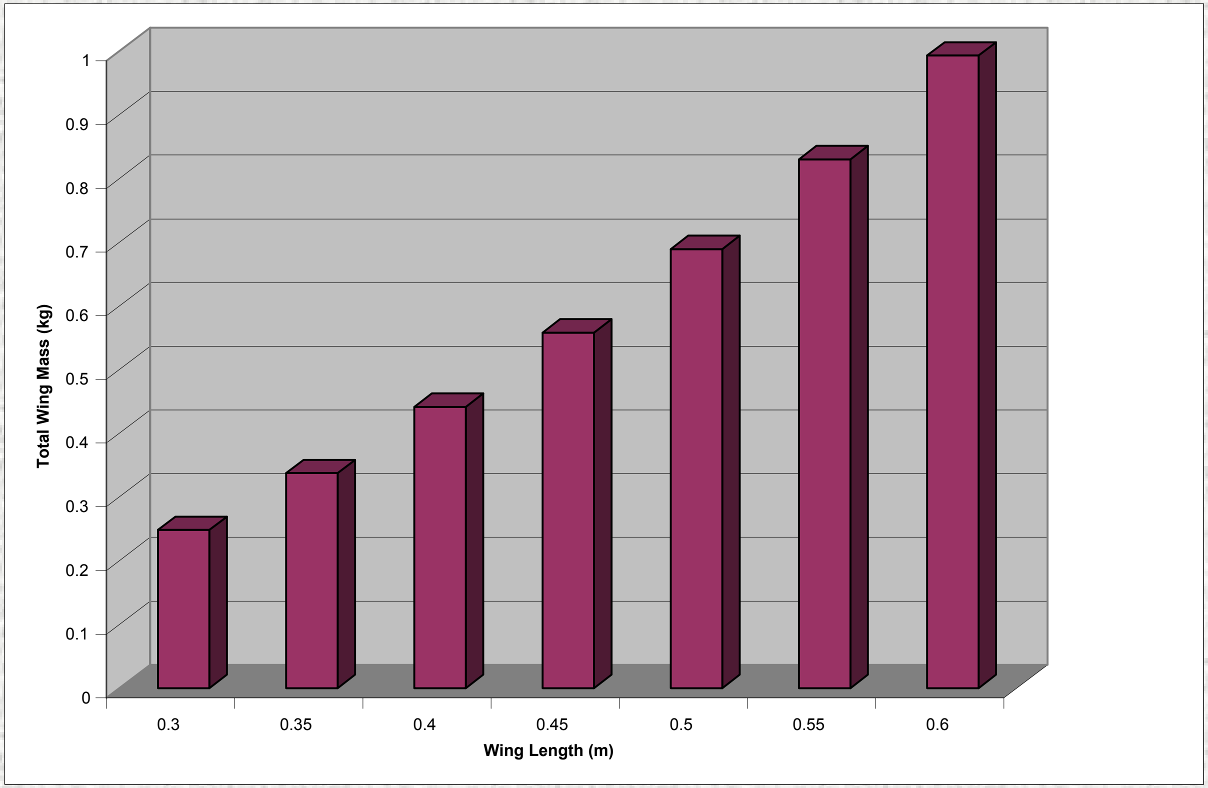


The motion from the horizontal to this maximum angle occurs in a time period of one fourth of one cycle (1/4f)

Wing Mass as a Function of Length

This example shows how wing mass increases with length

Wing mass was based on the structural analysis to resist the loading encountered and minimize the tip bending to no more then 1.5 cm

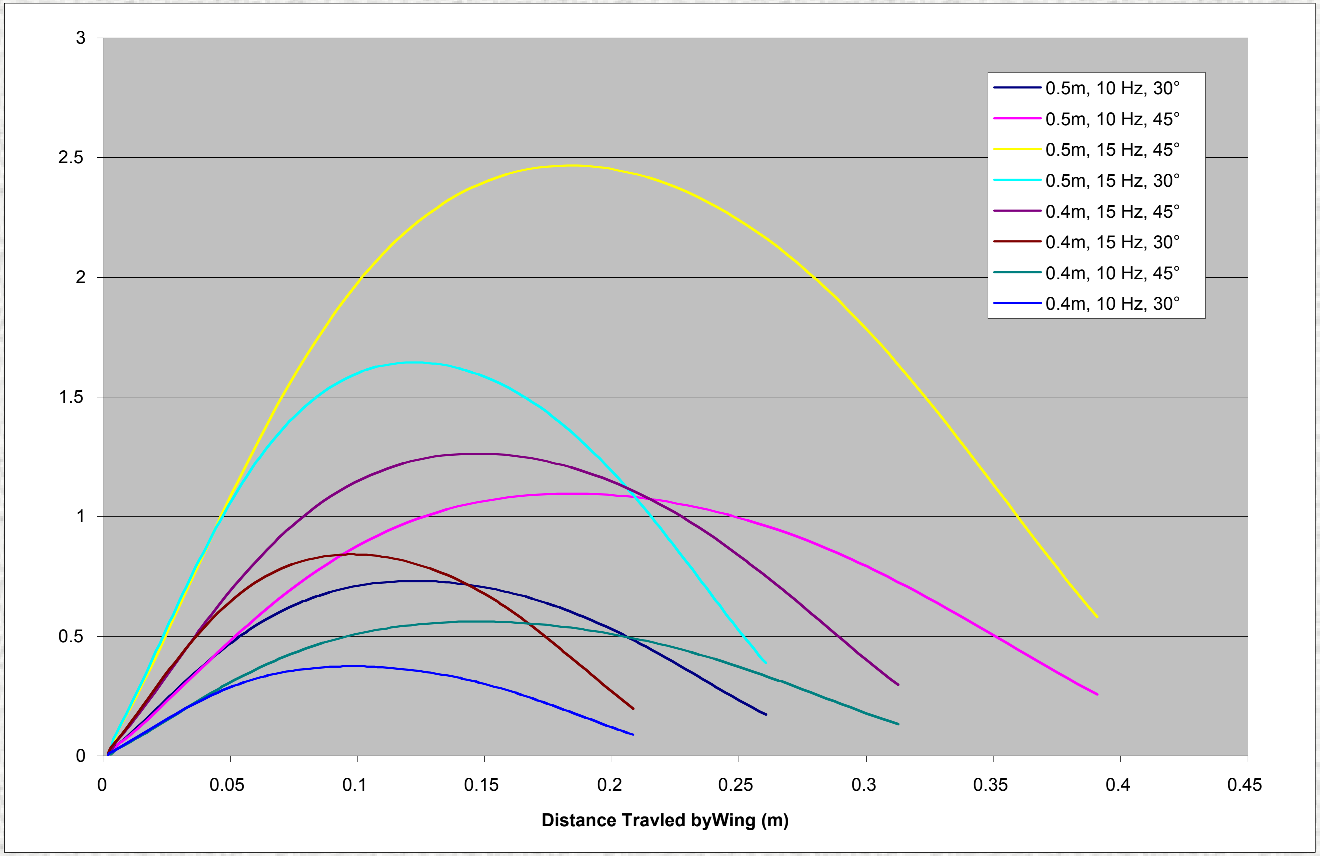


The relative mass capacity of the vehicle is the total mass the Entomopter can lift minus the wing mass.

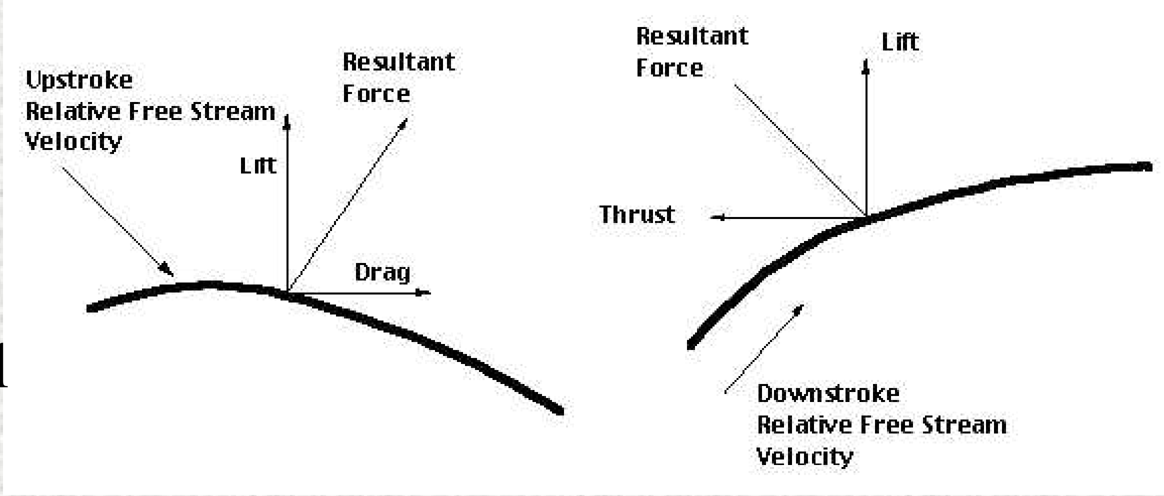
Force Required to Move the Wing

The force generated throughout 1/4 of the flap cycle is shown.

This figure attempts to demonstrate the complexity of the optimization process. Each variable combination can have a significant and varied effect on the force / power required to move the wing

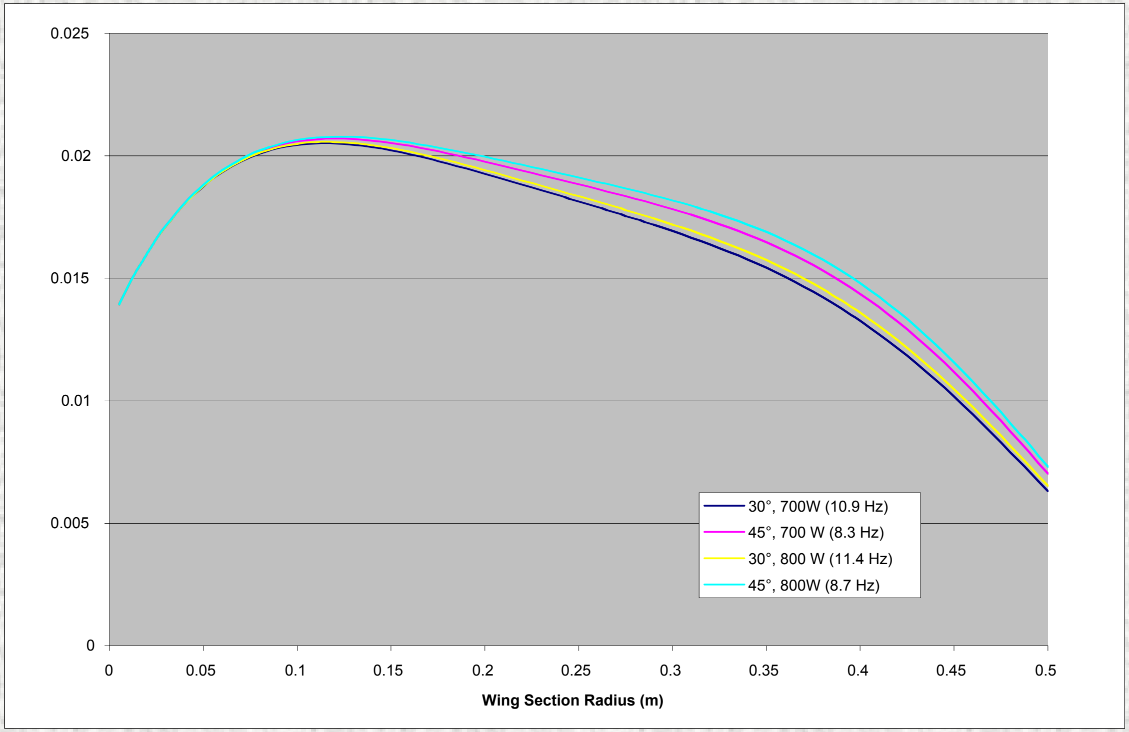


Lift Generated

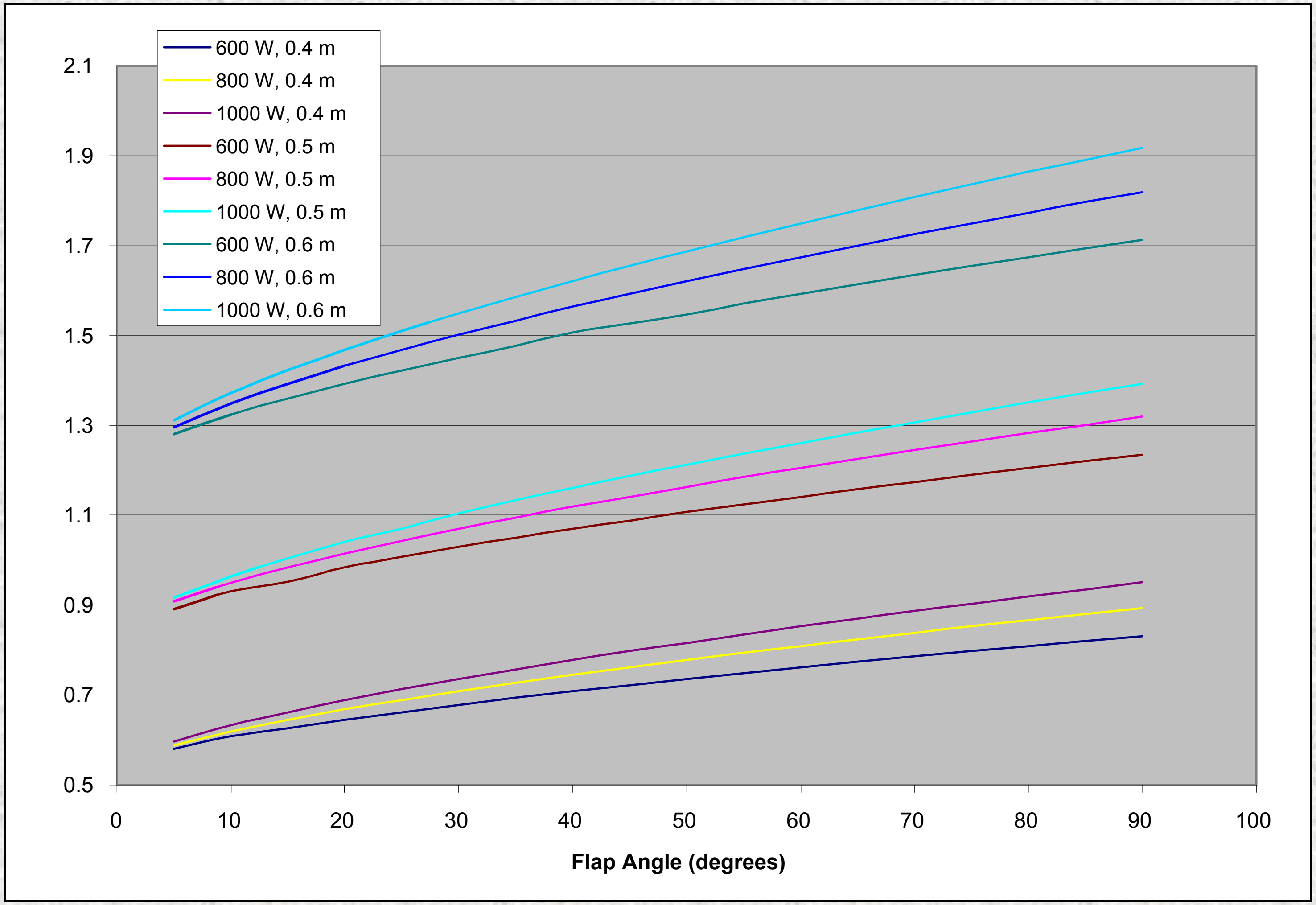


The lift generated is also effected by the operational characteristics of the wing (frequency, flap angle and length)

Lift generation along the wing length. It was determined for given power level more lift can be generated by flapping the wing through higher angles and reducing frequency



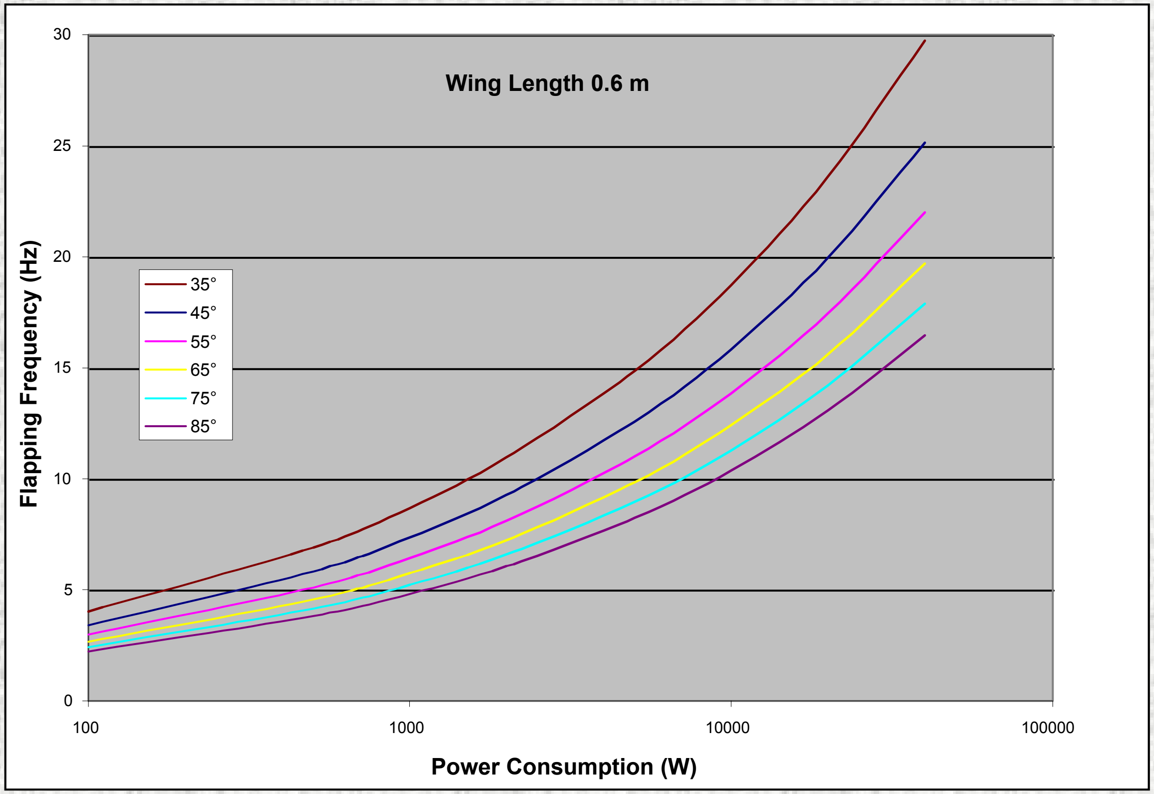
Relative Lifting Capacity as a Function of Flap Angle, Power Consumption and Wing Length



Power Consumption and Frequency

The flapping frequency has a significant effect on power consumption.

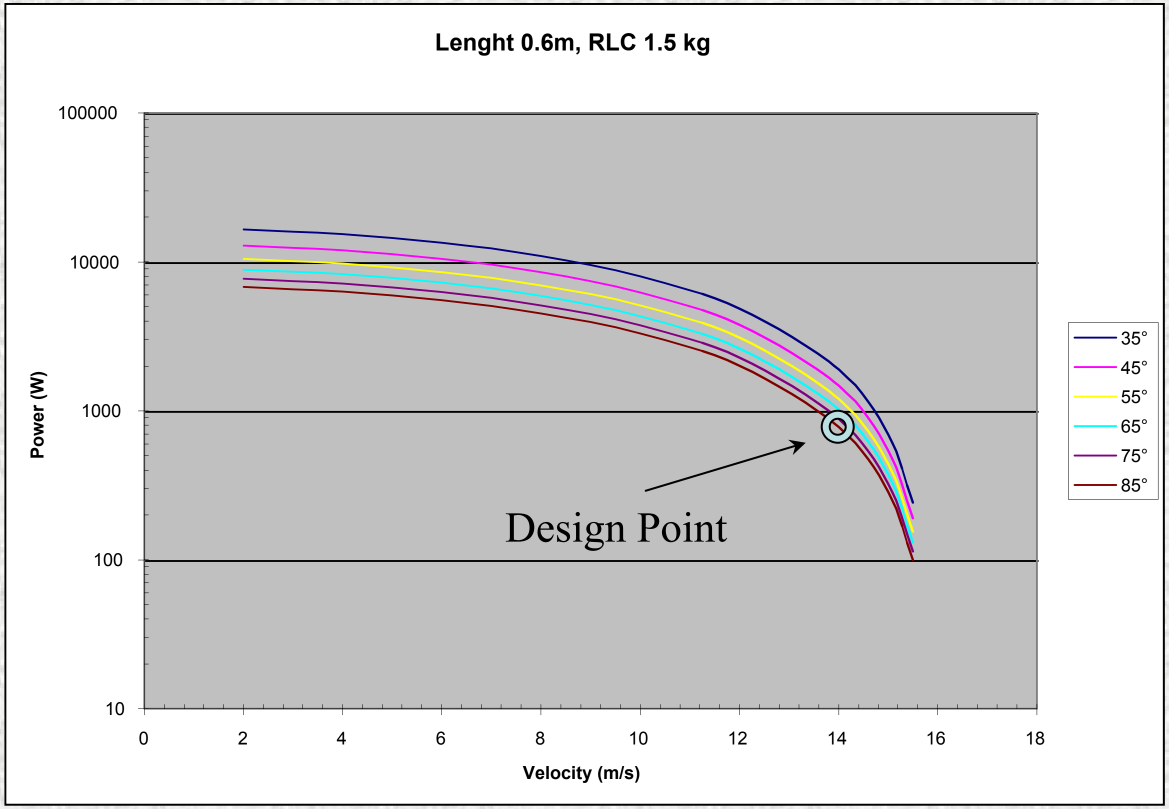
As the frequency increases for a given maximum flap angle and wing length, the required power increase exponentially



Design Point Under Cruise Conditions

Wing Cl 10.0
Flight Speed 14 m/s
Wing Section Length 0.6 m
Wing Flap Angle 75°
Flapping Frequency 6 Hz
Relative Lifting Capacity 1.5 kg
Engine Power 883 W
Fuel Consumption 0.011 kg/min

(for Hydrazine fuel, 0.1 kg for a 10 minute flight)



Landing

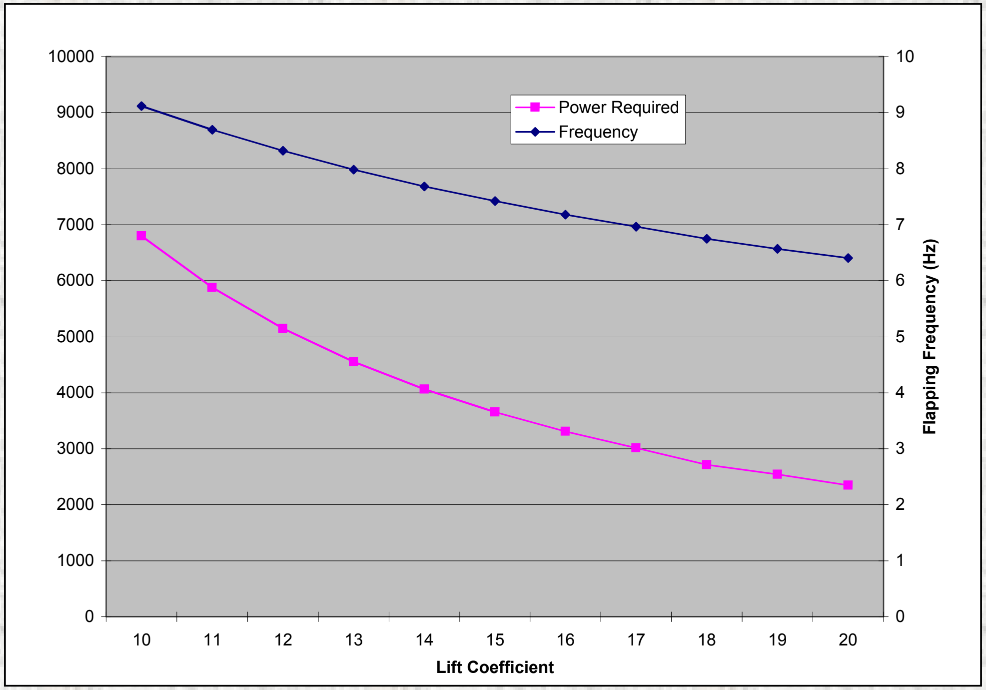
It takes considerably more power to land then for cruise.

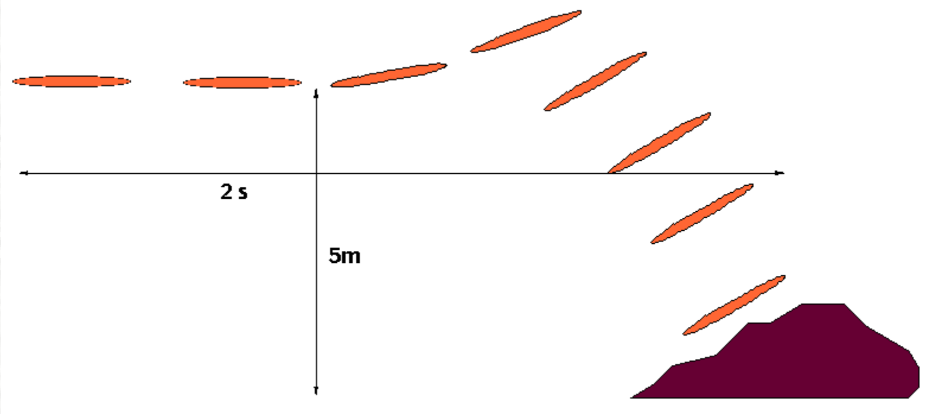
The landing sequence should last no more then 2 to 3 seconds

Landing can be achieved by over-speeding the engine thereby producing more power and exhaust gas.

The exhaust gas can be used to momentarily enhance lift.

The down side is fuel consumption greatly increases

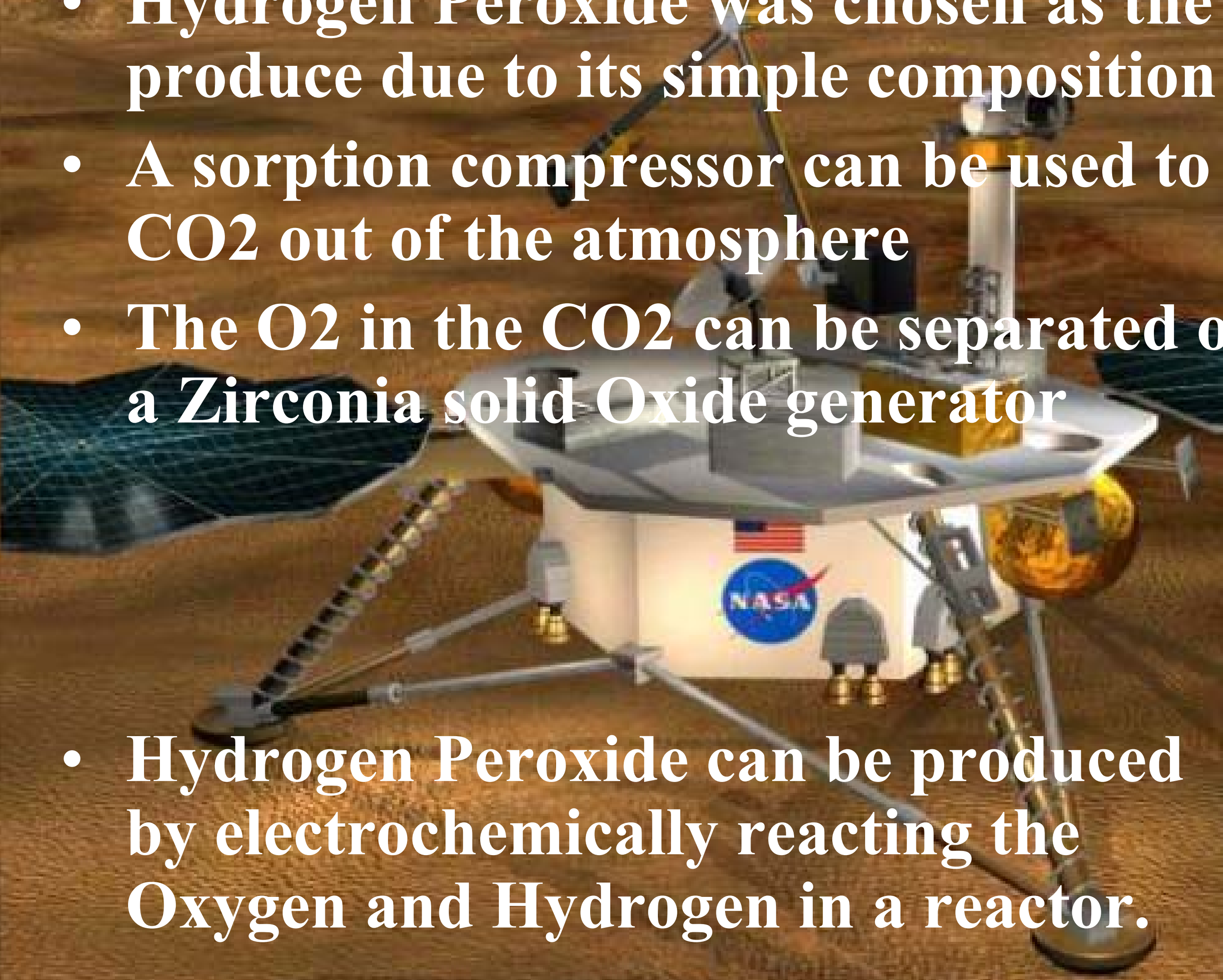




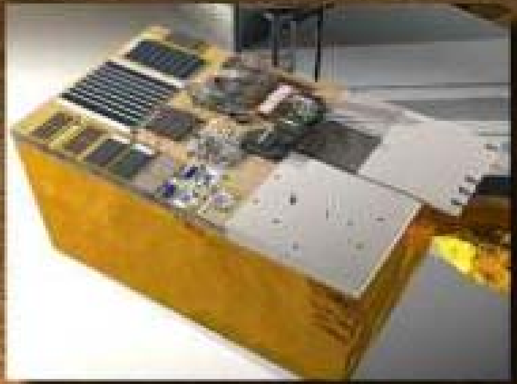
Fuel Selection

- Engine design and performance will depend on the type of fuel is used.
- Fuel can be made in-situ on the surface or brought from Earth
  - The applicable fuels will depend on which method is used.
  - This result can greatly affect engine design and vehicle performance
- Either Fuel or Hydrogen must be brought from Earth
  - Mission will be limited by either fuel carried or H_2 carried
  - Volumetric energy density of H_2 is very poor (8.4 MJ/L for liquid H_2 to 31.1 MJ/L for gasoline)
- A study was performed to evaluate the tradeoff between carrying fuel directly from Earth or manufacturing it on Mars
- The fuel consumption was estimated at 0.1 kg per day

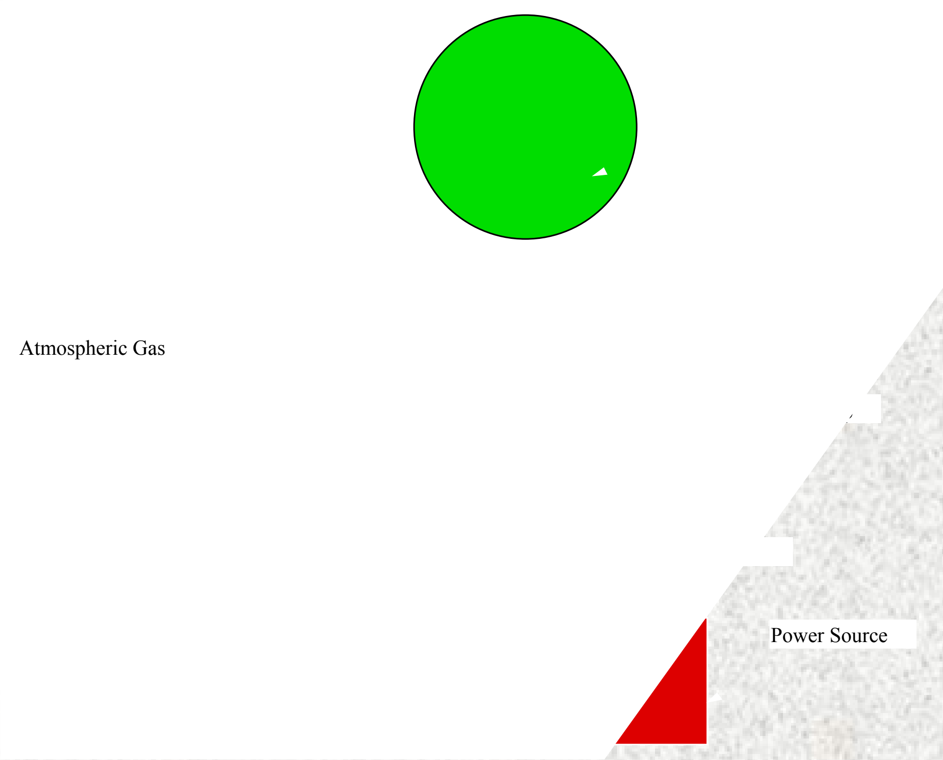
Propellant Production



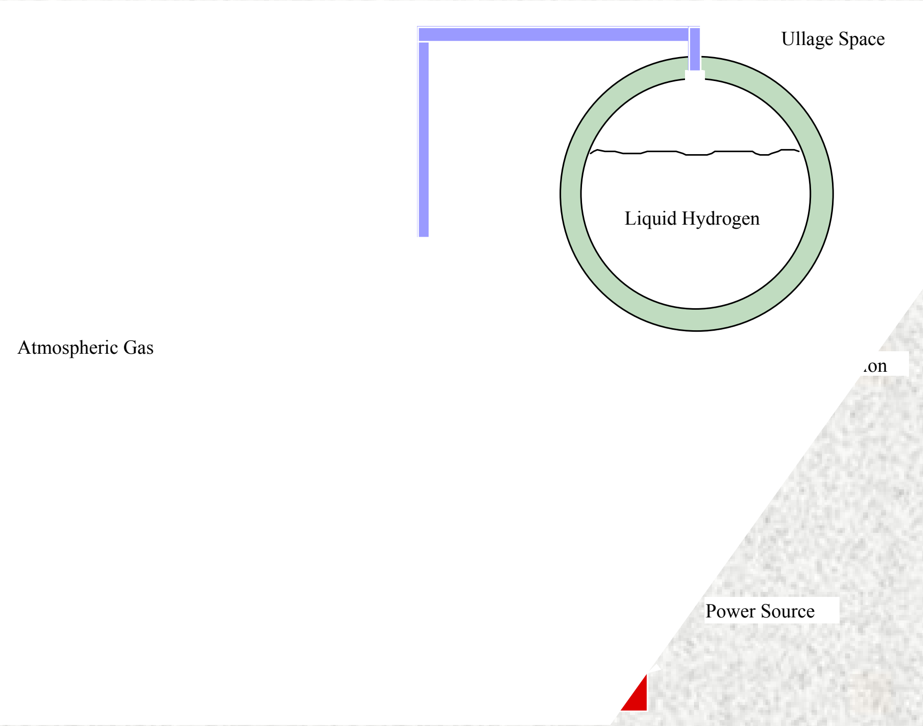
- Hydrogen Peroxide was chosen as the fuel to produce due to its simple composition (H_2O_2)
- A sorption compressor can be used to separate CO_2 out of the atmosphere
- The O_2 in the CO_2 can be separated out using a Zirconia solid Oxide generator
- Hydrogen Peroxide can be produced by electrochemically reacting the Oxygen and Hydrogen in a reactor.



Propellant Production Systems

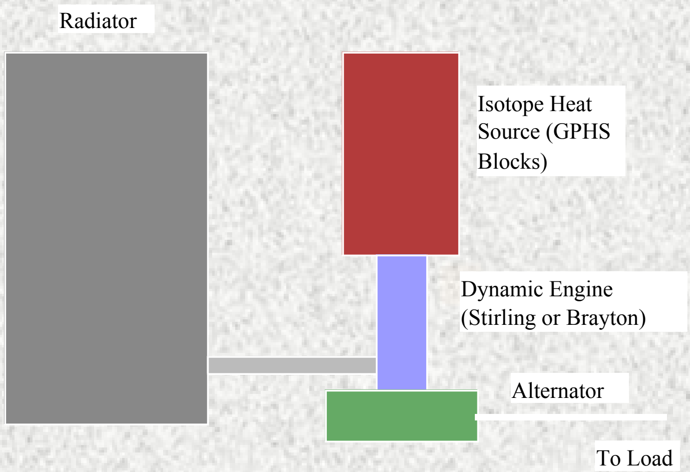


Gaseous H2 Storage System



Cryogenic H2 Storage System

Fuel System Power Source



Radiator

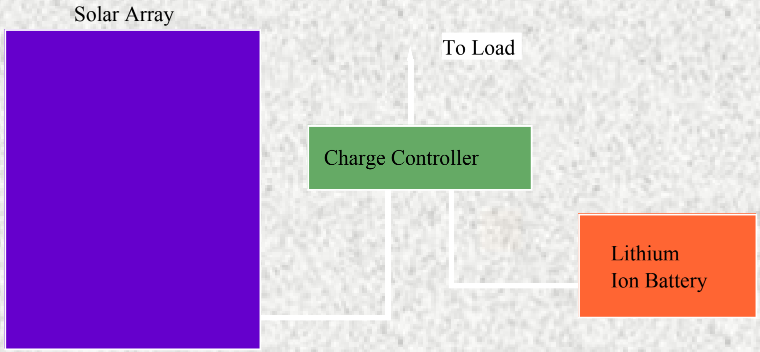
Isotope Heat Source (GPHS Blocks)

Dynamic Engine (Stirling or Brayton)

Alternator

To Load

Isotope System



Solar Array

To Load

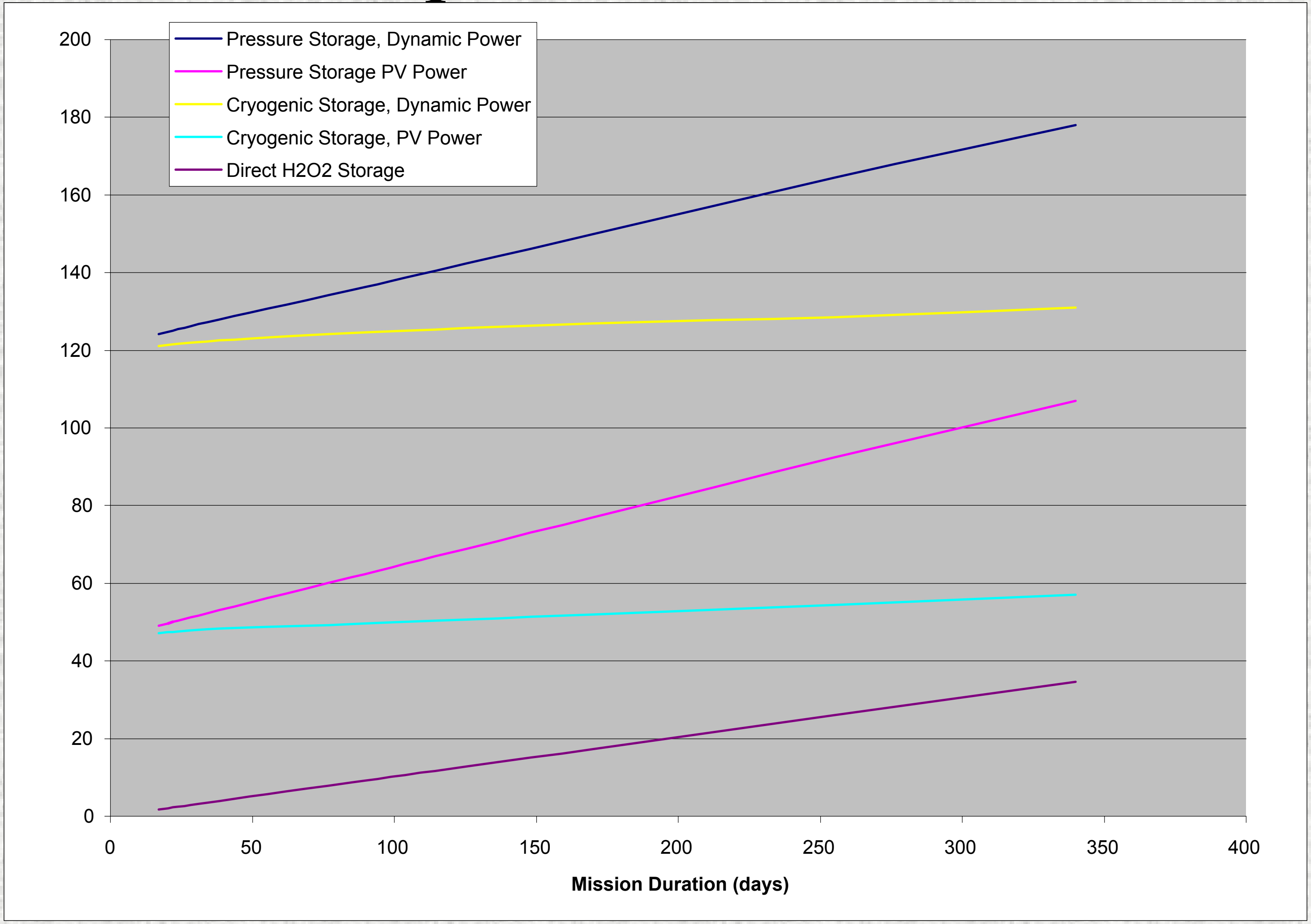
Charge Controller

Lithium Ion Battery

Photovoltaic / Battery System

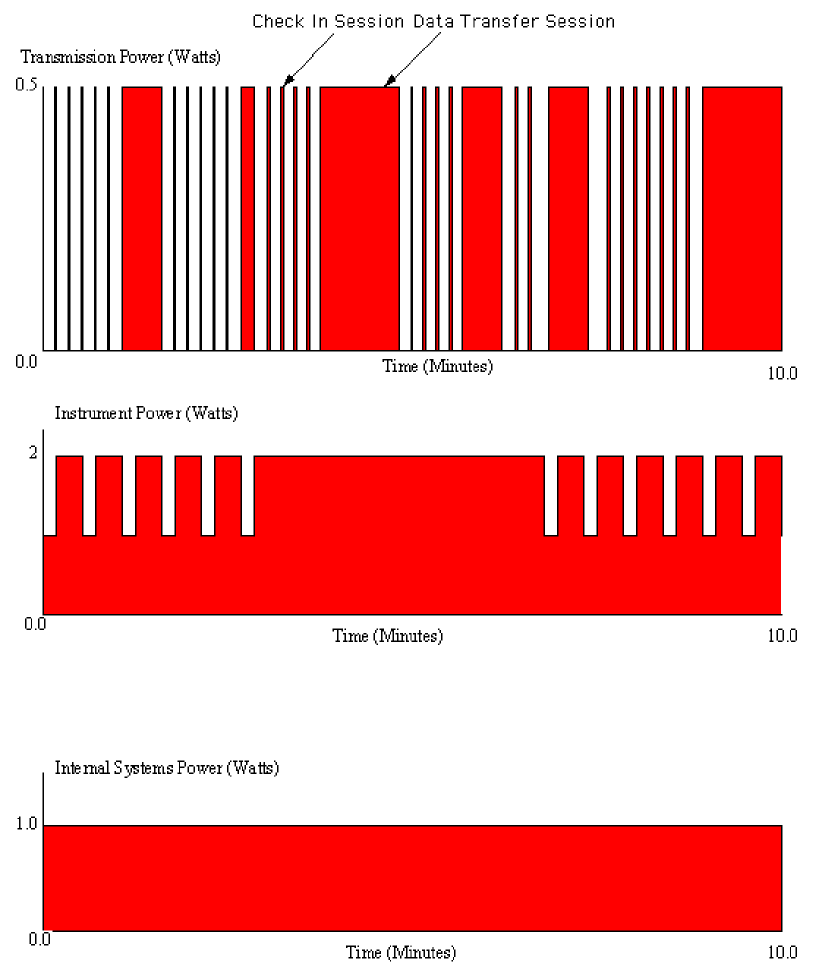
The power systems needed to run the fuel production plant was factored into the analysis

Mass Comparison between In-Situ Propellant Production and Transported Propellant from Earth



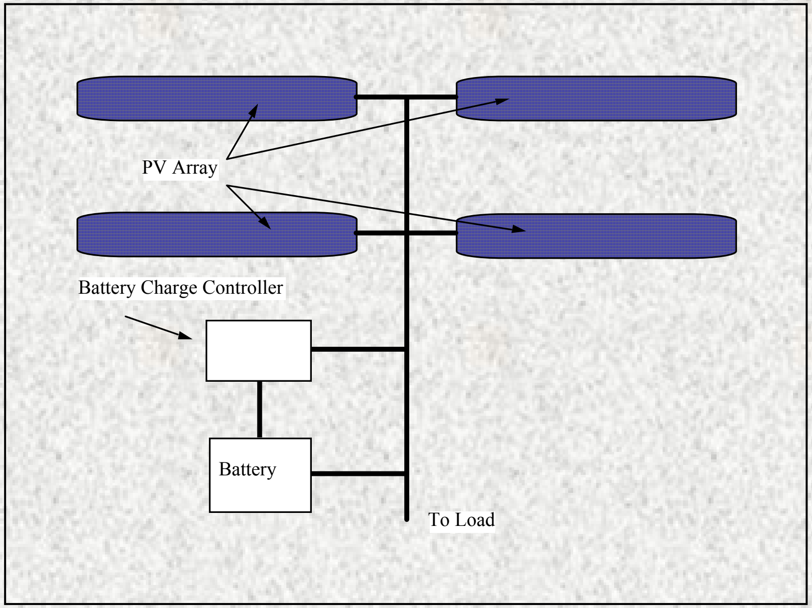
Power Production Requirements

- Communications
  - 0.5 Watt peak
  - 3 W-hr total energy
- Science Instruments
  - 2 Watts peak
  - 10.7 W-hr total
- Internal Computer Systems
  - 1 Watt continuous
  - 6 W-hr total



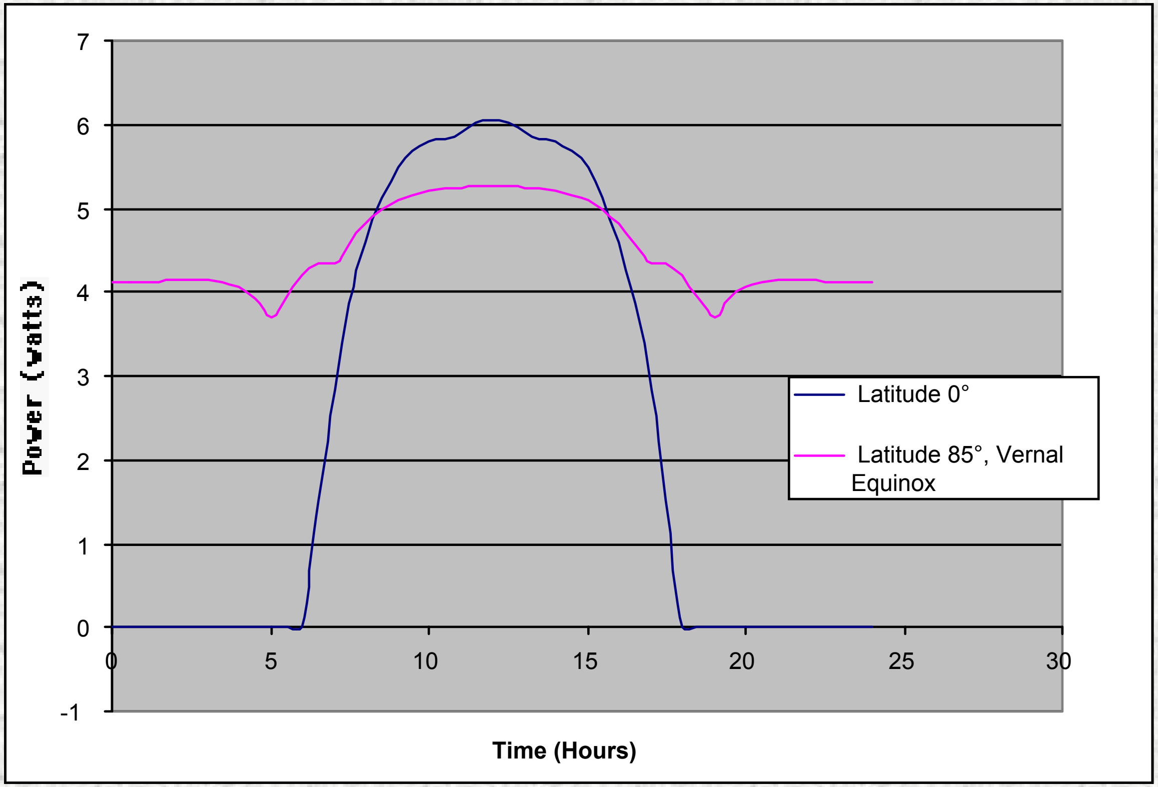
Photovoltaic/Battery Power System

- This system was the most attractive based on performance and weight.
- Consists of $CuInSe^2$ thin film array on the wings with a Lithium Polymer battery for storage.
- Array Performance
  - 10% efficient
  - 0.20 m^2 area
  - Array Mass 0.014 kg
- Battery Performance
  - 6.5 W-hr capacity
  - Battery Mass 0.048 kg
- Estimated system mass 0.068 kg

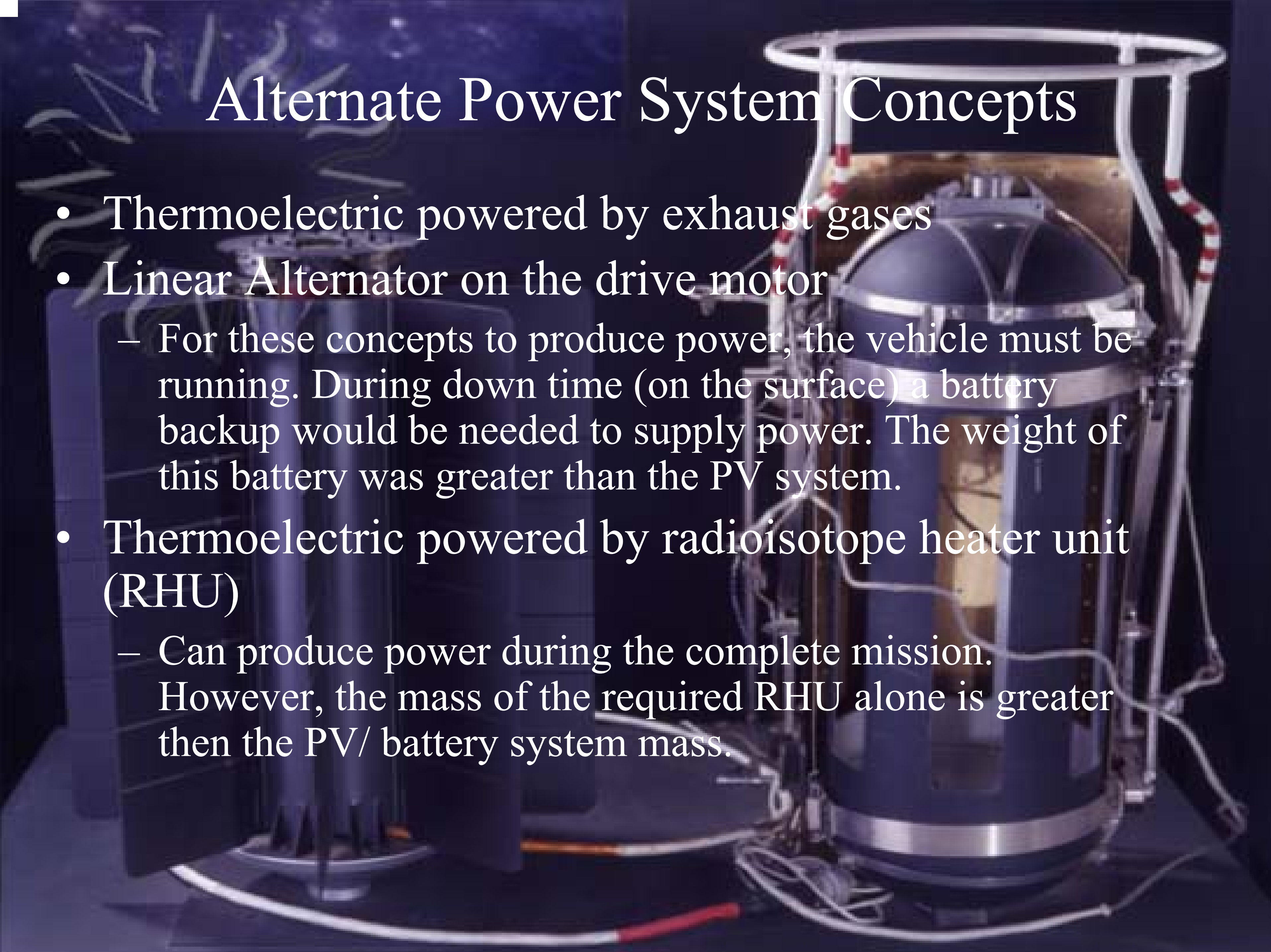


Array Performance

- Equator
  - – 55.71 W-hr
- 85° N Latitude
  - – 107.67 W-hr



Alternate Power System Concepts



- Thermoelectric powered by exhaust gases
- Linear Alternator on the drive motor
  - For these concepts to produce power, the vehicle must be running. During down time (on the surface) a battery backup would be needed to supply power. The weight of this battery was greater than the PV system.
- Thermoelectric powered by radioisotope heater unit (RHU)
  - Can produce power during the complete mission. However, the mass of the required RHU alone is greater then the PV/ battery system mass.

Entomopter Flight System for Mars

- Exploration in conjunction with a rover vehicle
  - Pro: Extended terrain coverage as the rover moves across the surface, enhancing navigation of the rover, potential to refuel with multiple flight capability, capability to bring back samples to the rover for analysis
  - Con: Increased logistical complexity

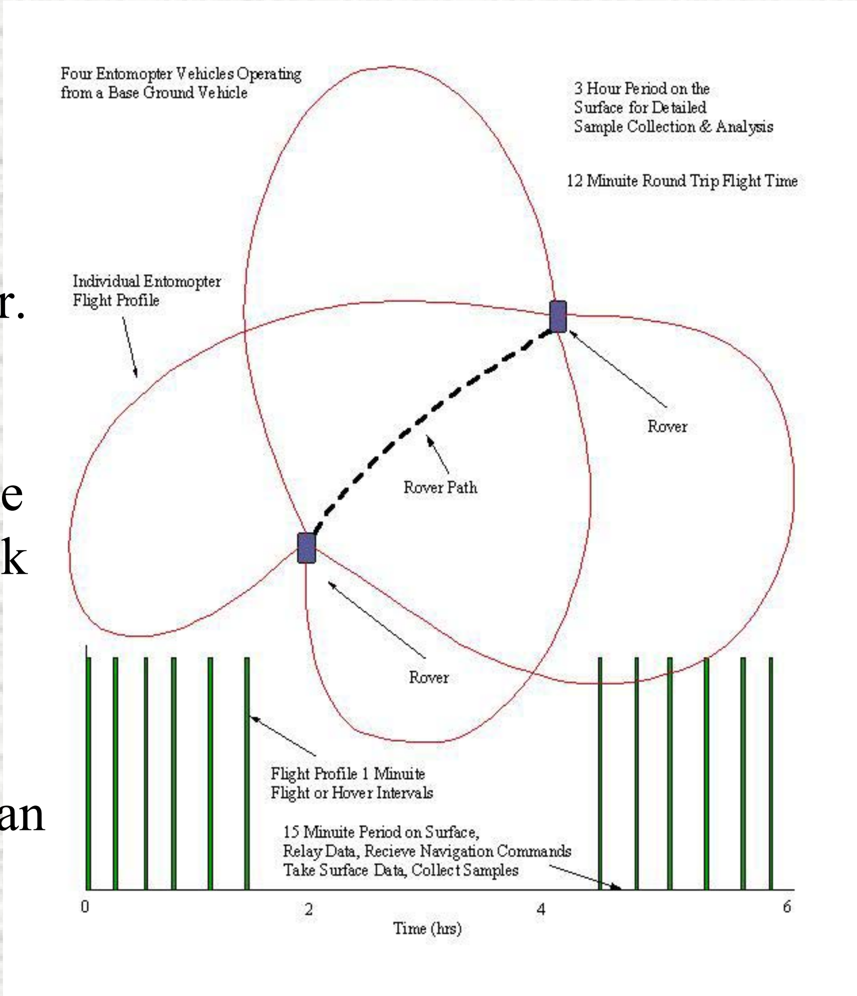
Mission Architecture

The Entomopter works in conjunction with a rover. The rover is used for refueling, as a communications / navigation hub and as a depository for scientific data collected.

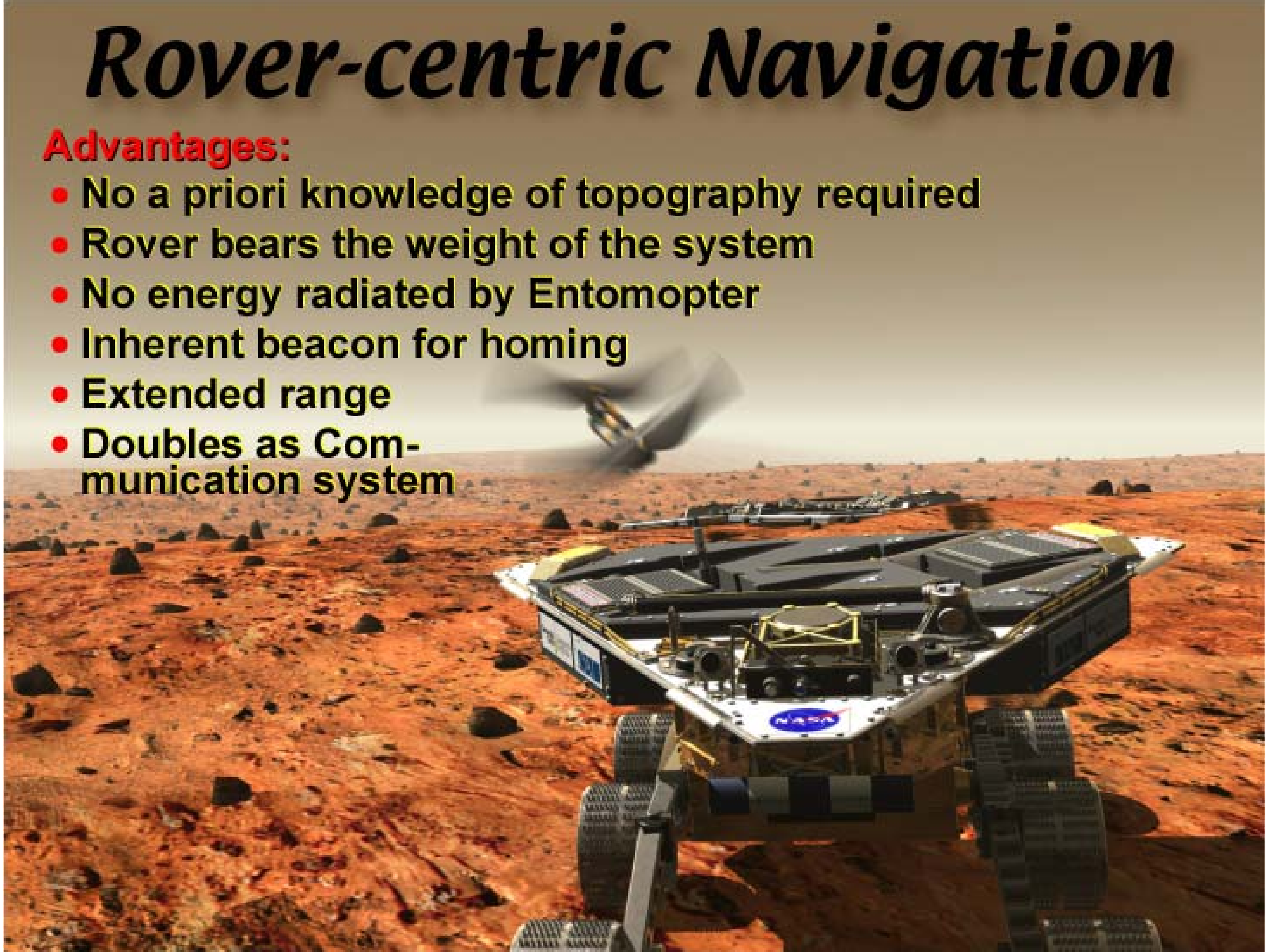
Navigation: The entomopter can scout out ahead to guide the rover. The rover is also used as a reference point for the entomopter.

Science: Science data is collected by the entomopter and transferred to the rover. The rover performs analysis and relays data back to earth.

Payload: The entomopter can change out science instruments while on the rover. It can also carry small science or other types of payloads and deposit them at specified locations on the surface.



Rover-centric Navigation



Advantages:

- No a priori knowledge of topography required
- Rover bears the weight of the system
- No energy radiated by Entomopter
- Inherent beacon for homing
- Extended range
- Doubles as Communication system

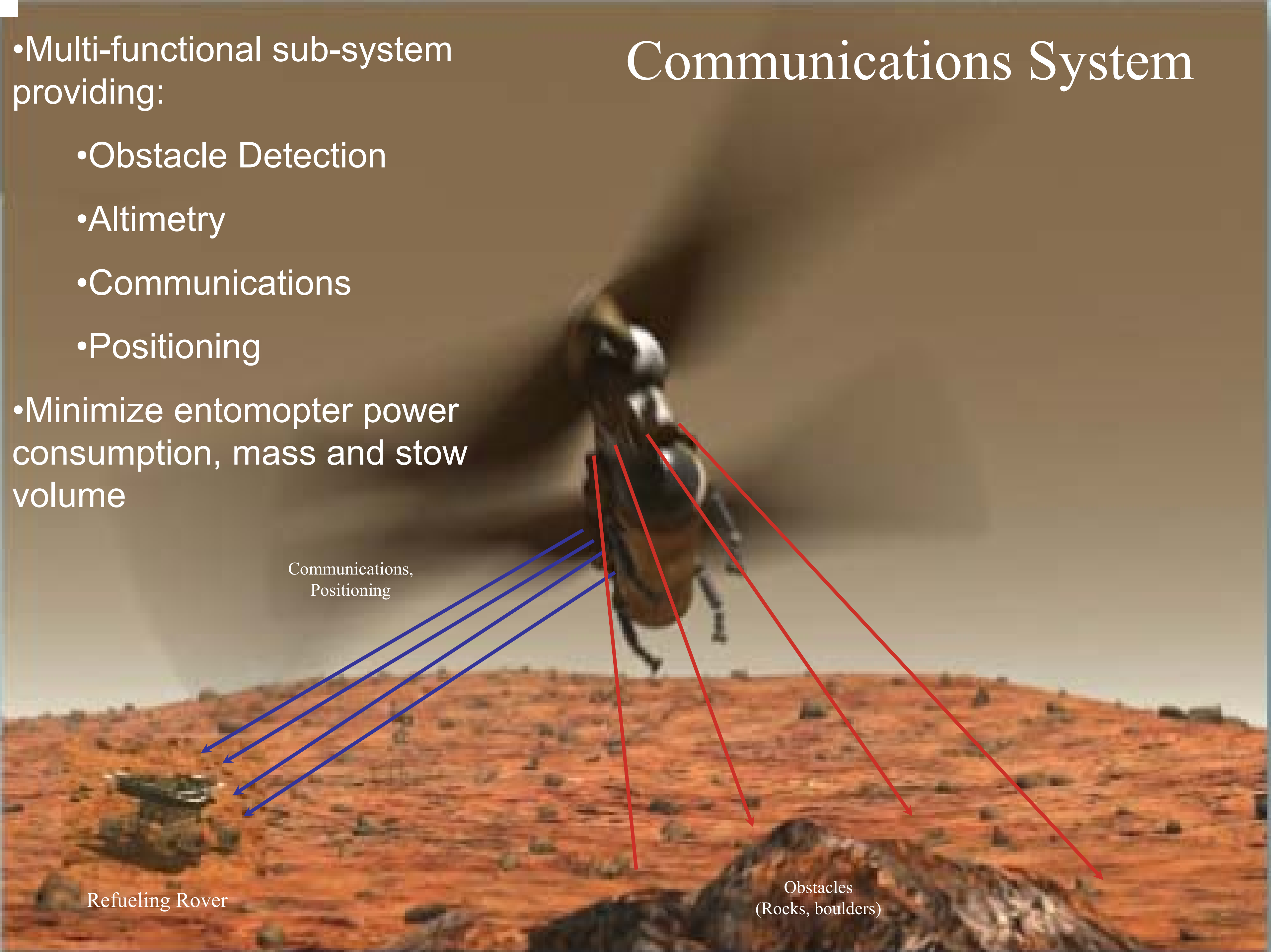
Rover-centric Navigation

How it works: Rover-born range-gated Doppler radar tells each Entomopter its relative position to the rover, other Entomopters, and detected obstacles. Range, azimuth, elevation, and velocity information is sent to each Entomopter as well as a map of nearby obstacles. The radar provides not only an inherent homing beacon, but bidirectional communication through direct transmission from the rover and electronic signature modulation of the return by the Entomopter.

The Doppler signature of the Entomopter is unique in the Mars environment, thereby facilitating tracking.

Communications System

- Multi-functional sub-system providing:
  - Obstacle Detection
  - Altimetry
  - Communications
  - Positioning
- Minimize entomopter power consumption, mass and stow volume



Communication Method

- Extremely short, wideband, rapid sequences of radio frequency (RF) energy can be used for a host of desired purposes, including communications, collision avoidance, positioning and altimetry.
- Multifunctional subsystem used by entomopter and rover in hybrid manner to perform multi- functions with single subsystem

Application	Range	Power Peak / Average
Communication at 1 kbit/sec	200 m 1000 m	132 nW / 39.5 mW 3.3 µW / 986.6 mW
Altimetry	10 m 200 m	1.6 pW / 3.9 µW 252 nW / 630 mW
Obstacle Avoidance	15 m 200 m	8 pW / 2.4 µW 254 nW / 76 mW

Linearly tapered slot antenna (LTSA) circular array (sunflower antenna)

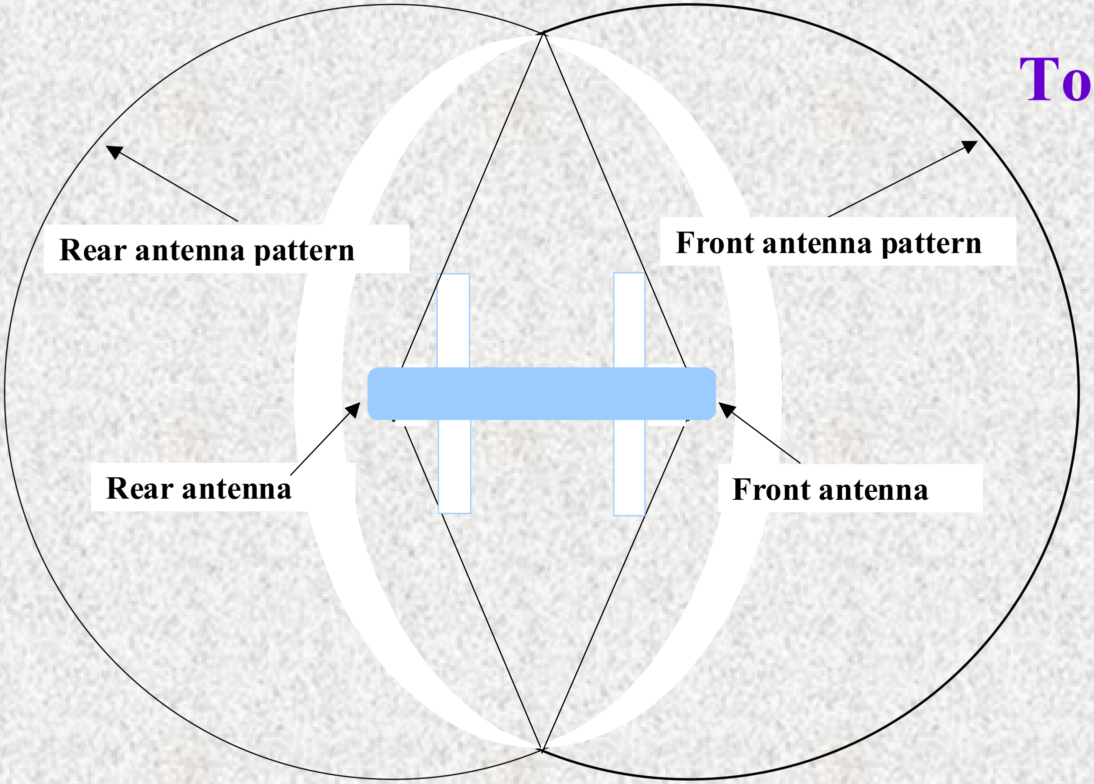
Endfire radiation providing omnidirectional pattern

Two halves mounted on entomopter without ground plane – no displacement about horizon

Entire sunflower could be mounted on rover with ground plane – desired displacement about horizon

Operates at high frequency - 18 GHz
Characteristics: Small / Lightweight
Reduced Scattering Losses
Increased Atmospheric and Dust Losses

Antenna Patterns



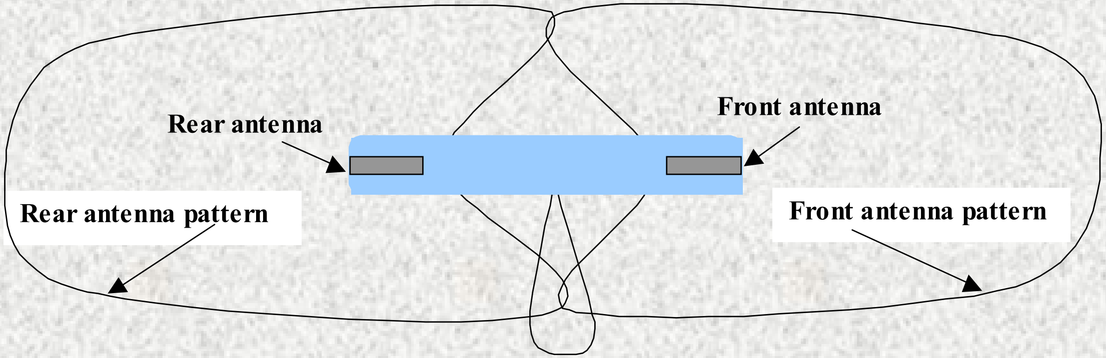
Rear antenna pattern

Front antenna pattern

Rear antenna

Front antenna

Top view of entomopter



Rear antenna

Front antenna

Rear antenna pattern

Front antenna pattern

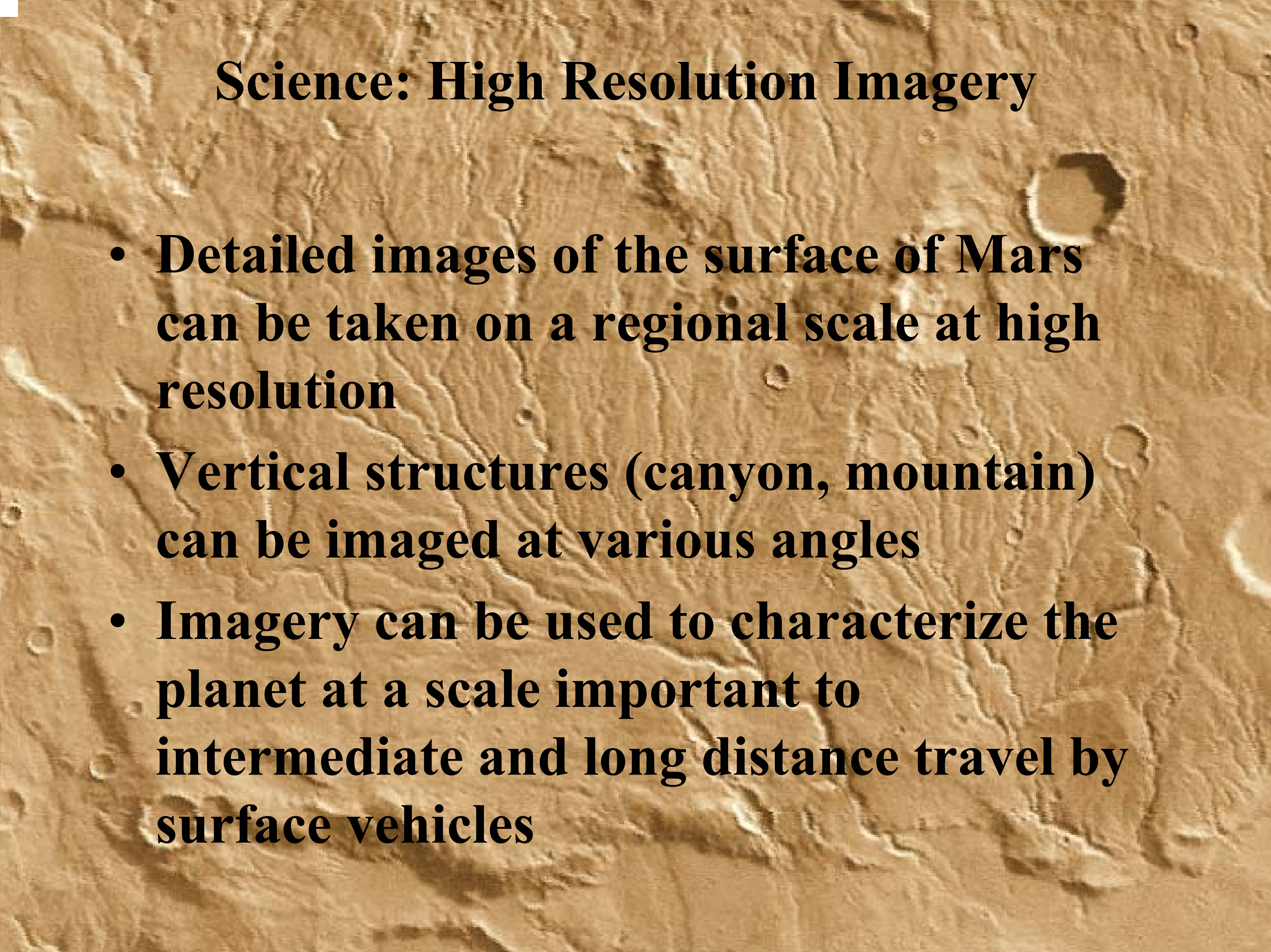
Side view of entomopter

Propagation Losses

- Atmospheric gaseous attenuation by water vapor and oxygen
- Dust storms
  - Planet-encircling storms believed to encompass the planet at some latitude
  - Regional storms include clouds and hazes with spatial dimension greater than 2000 km
  - Local dust storms include clouds and hazes with spatial dimensions less than 2000 km
  - Ka-band, large dust storms cause ~ 0.3 dB/km loss and normal dust storms cause ~ 0.1 dB/km
- Scattering loss
  - Scattering of signal from sharp discontinuities in objects in signal path

Atmospheric attenuation by water vapor and oxygen at Earth and Mars surface

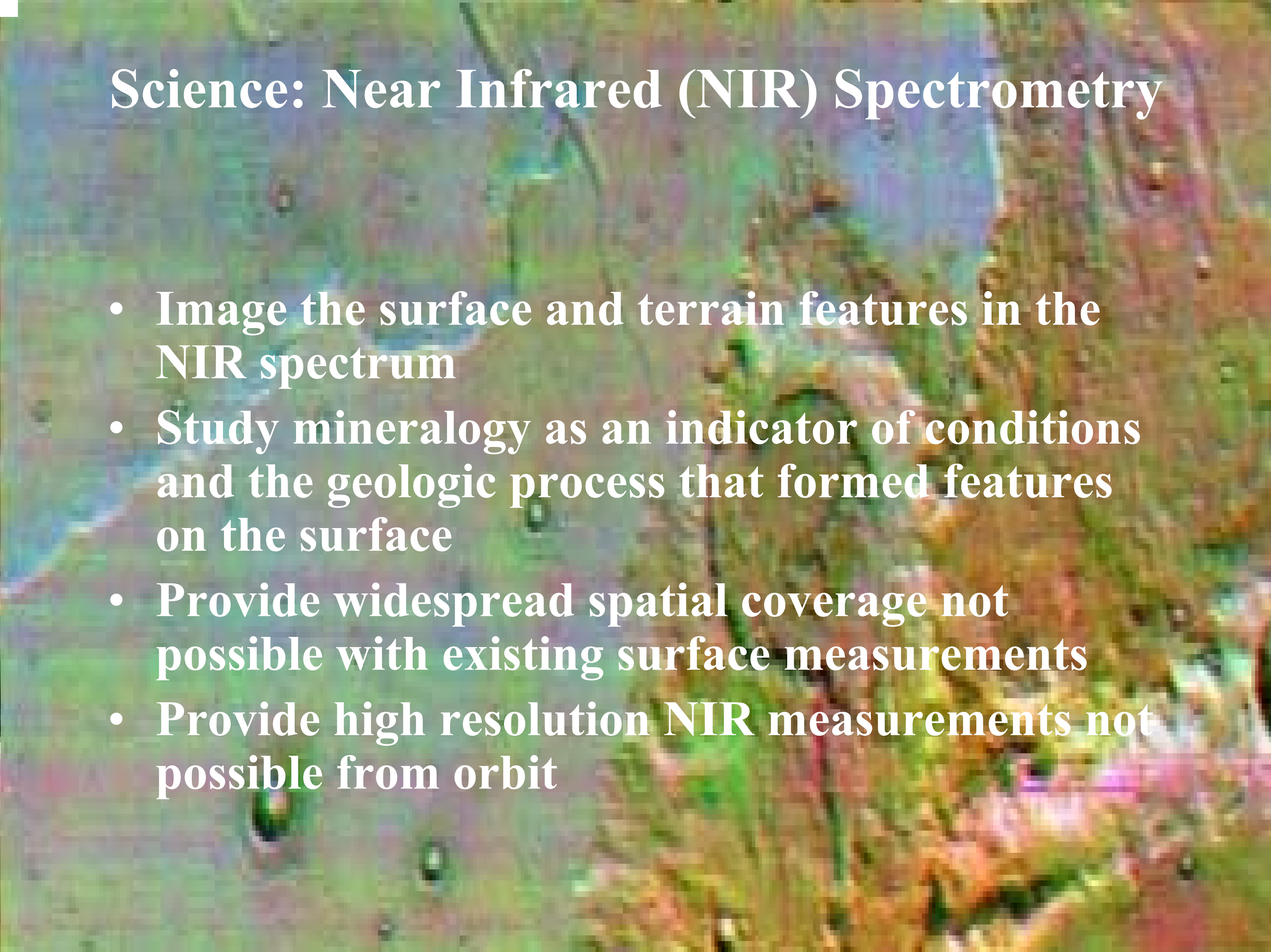
Entomopter Mission Simulation



Science: High Resolution Imagery

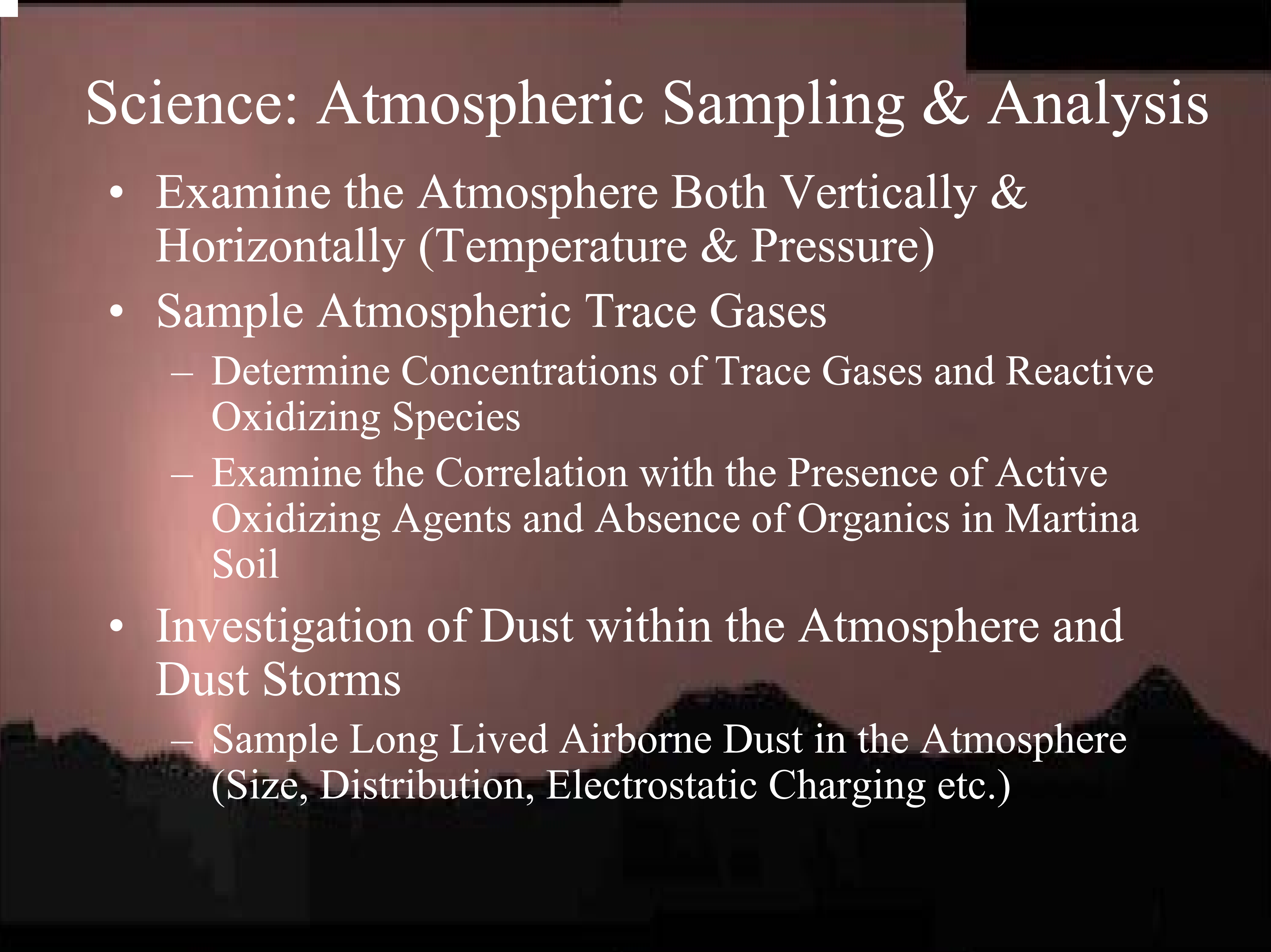
- Detailed images of the surface of Mars can be taken on a regional scale at high resolution
- Vertical structures (canyon, mountain) can be imaged at various angles
- Imagery can be used to characterize the planet at a scale important to intermediate and long distance travel by surface vehicles

Science: Near Infrared (NIR) Spectrometry



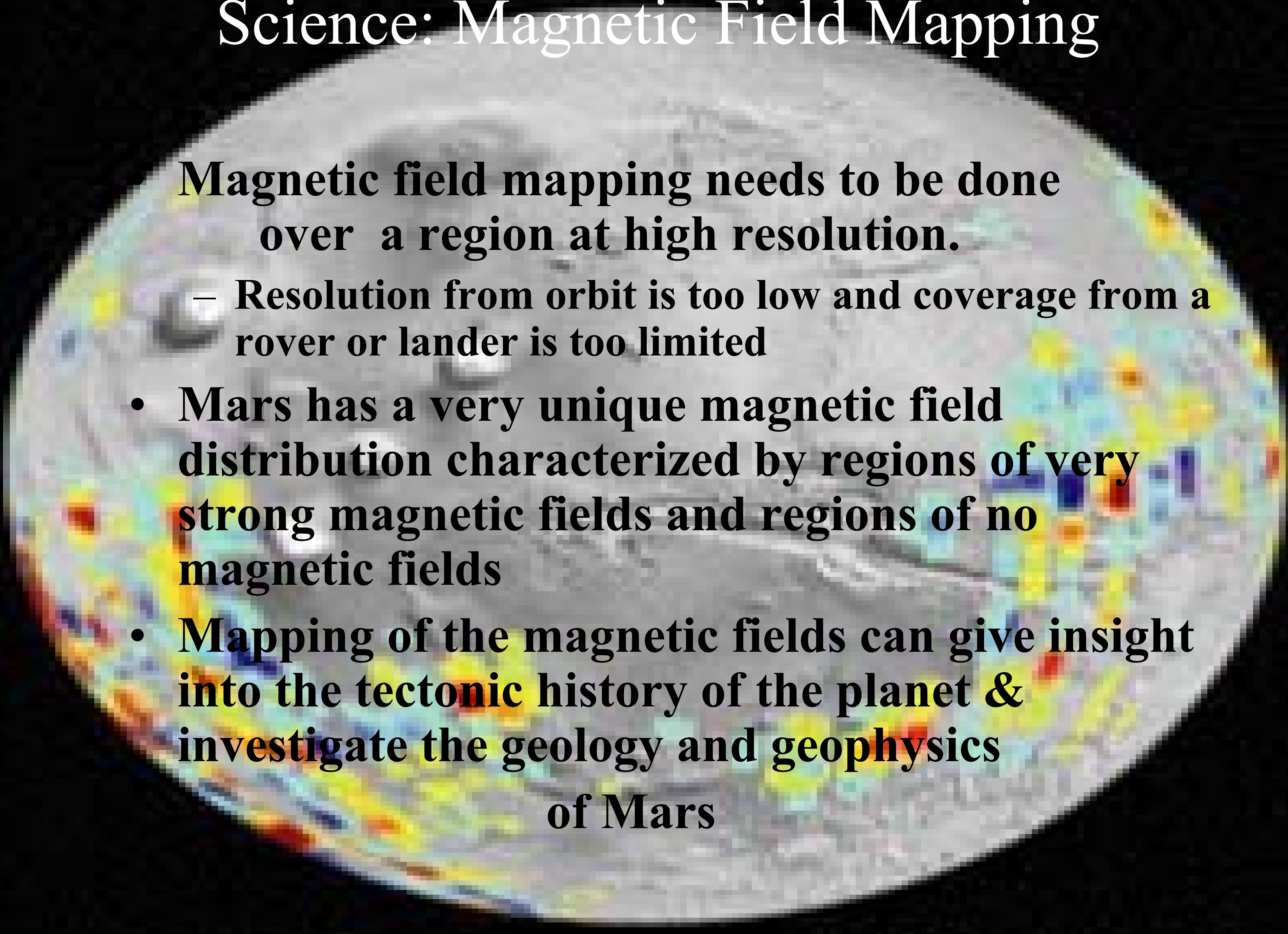
- Image the surface and terrain features in the NIR spectrum
- Study mineralogy as an indicator of conditions and the geologic process that formed features on the surface
- Provide widespread spatial coverage not possible with existing surface measurements
- Provide high resolution NIR measurements not possible from orbit

Science: Atmospheric Sampling & Analysis



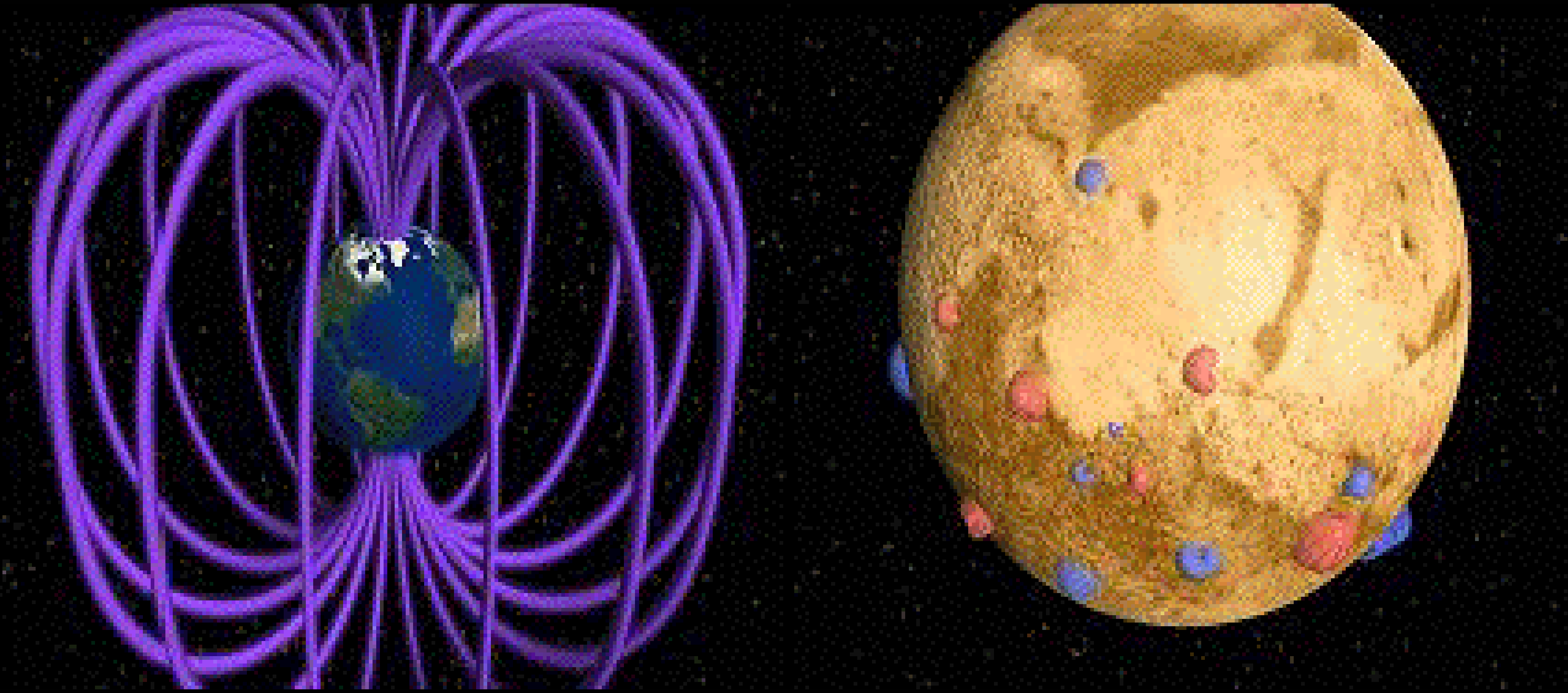
- Examine the Atmosphere Both Vertically & Horizontally (Temperature & Pressure)
- Sample Atmospheric Trace Gases
  - Determine Concentrations of Trace Gases and Reactive Oxidizing Species
  - Examine the Correlation with the Presence of Active Oxidizing Agents and Absence of Organics in Martina Soil
- Investigation of Dust within the Atmosphere and Dust Storms
  - Sample Long Lived Airborne Dust in the Atmosphere (Size, Distribution, Electrostatic Charging etc.)

Science: Magnetic Field Mapping

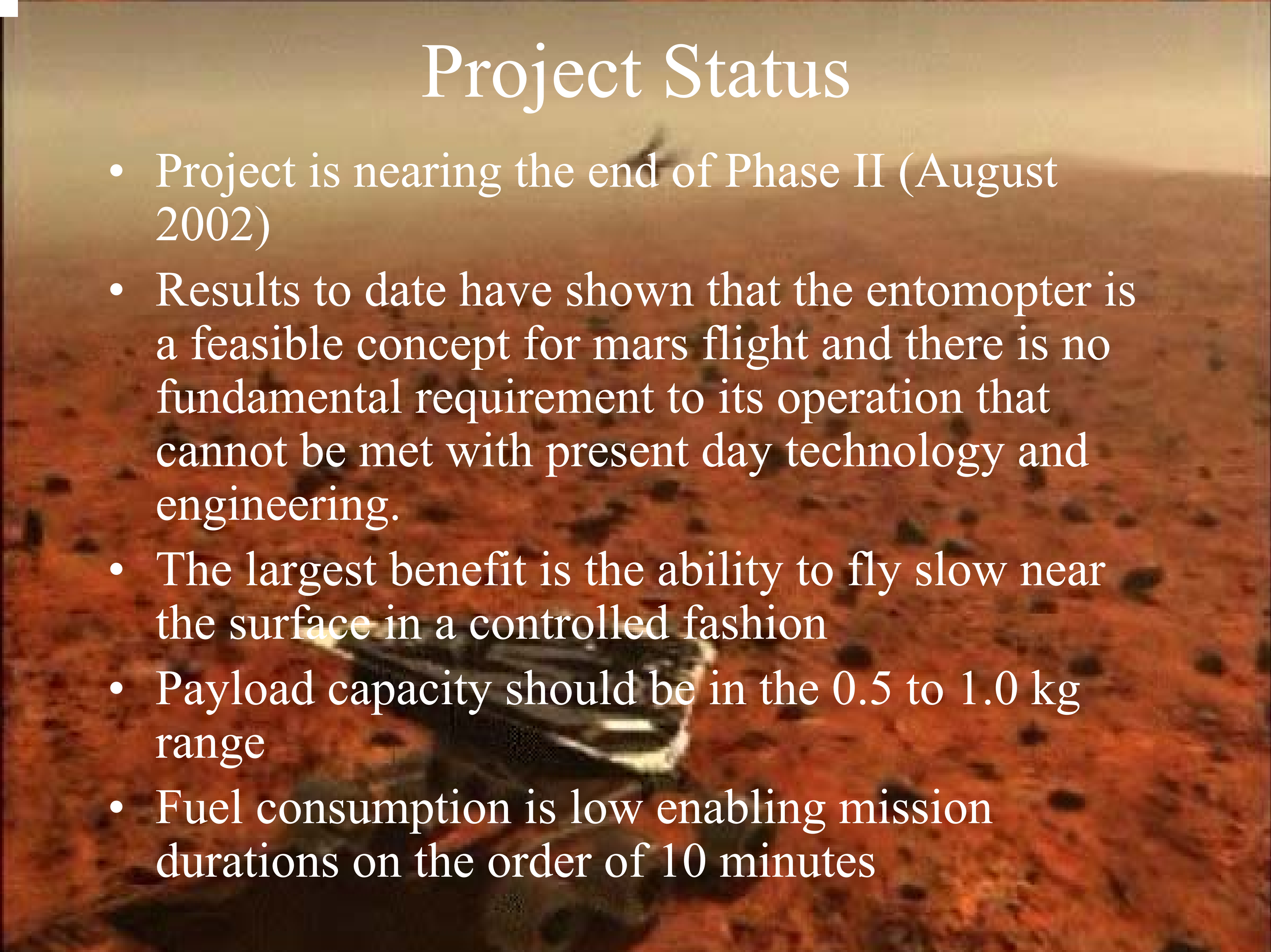


- Magnetic field mapping needs to be done over a region at high resolution.
  - Resolution from orbit is too low and coverage from a rover or lander is too limited
- Mars has a very unique magnetic field distribution characterized by regions of very strong magnetic fields and regions of no magnetic fields
- Mapping of the magnetic fields can give insight into the tectonic history of the planet & investigate the geology and geophysics of Mars

Magnetic Field Comparison Between Earth and Mars



Project Status



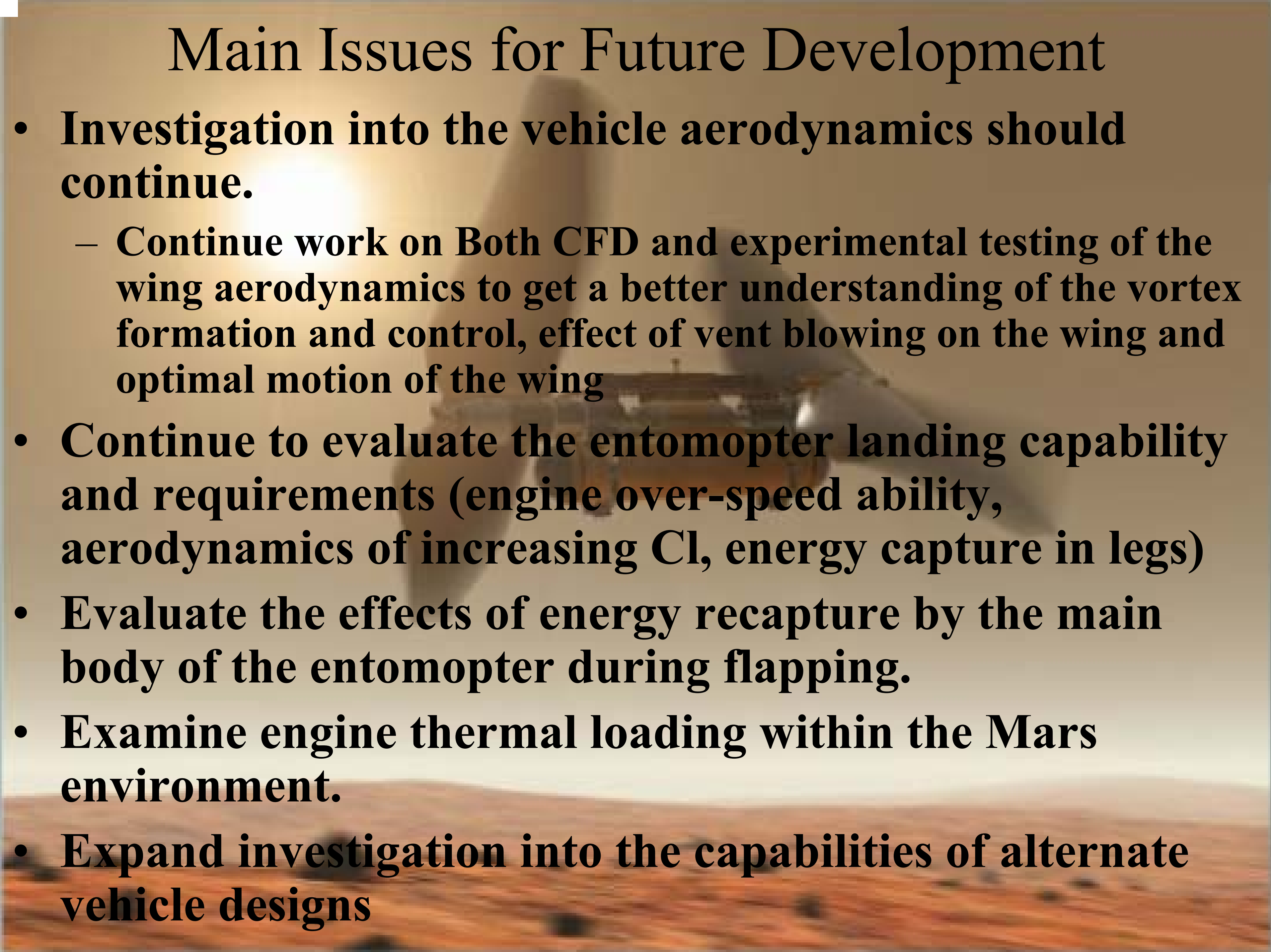
- Project is nearing the end of Phase II (August 2002)
- Results to date have shown that the entomopter is a feasible concept for mars flight and there is no fundamental requirement to its operation that cannot be met with present day technology and engineering.
- The largest benefit is the ability to fly slow near the surface in a controlled fashion
- Payload capacity should be in the 0.5 to 1.0 kg range
- Fuel consumption is low enabling mission durations on the order of 10 minutes

Alternate Vehicle Designs

- Focus to date has been on the GTRI entomopter design, however other potential designs may also be applicable
- Electrically powered vehicle based on an Ionic Polymer Metal Composite (IOPC) looks promising
  - Advantages: No mechanisms needed to move the wings, eliminates the need for fuel, system can be recharged enabling extended mission operation
  - Disadvantages: Lower achievable wing lift coefficient due to the absence of exhaust gas for boundary layer lift augmentation

From Dr. Shahinpoor University of New Mexico

IOPC Wing Motion Demonstration



Main Issues for Future Development

- **Investigation into the vehicle aerodynamics should continue.**
  - **Continue work on Both CFD and experimental testing of the wing aerodynamics to get a better understanding of the vortex formation and control, effect of vent blowing on the wing and optimal motion of the wing**
- **Continue to evaluate the entomopter landing capability and requirements (engine over-speed ability, aerodynamics of increasing Cl, energy capture in legs)**
- **Evaluate the effects of energy recapture by the main body of the entomopter during flapping.**
- **Examine engine thermal loading within the Mars environment.**
- **Expand investigation into the capabilities of alternate vehicle designs**