Exploring Venus

Geoffrey A. Landis

With a temperature higher than the inside of your oven and atmospheric pressure equal to that a kilometer under the ocean, the surface of Venus is one of the most hostile environments in the solar system, and Venus exploration presents a challenge to technology. This lecture presents mission trade-offs and discusses a proposed mission concept for rover and aircraft based exploration of the surface and atmosphere of Venus. Several approaches to the technology, electronics, mechanical parts, and power systems, are discussed.


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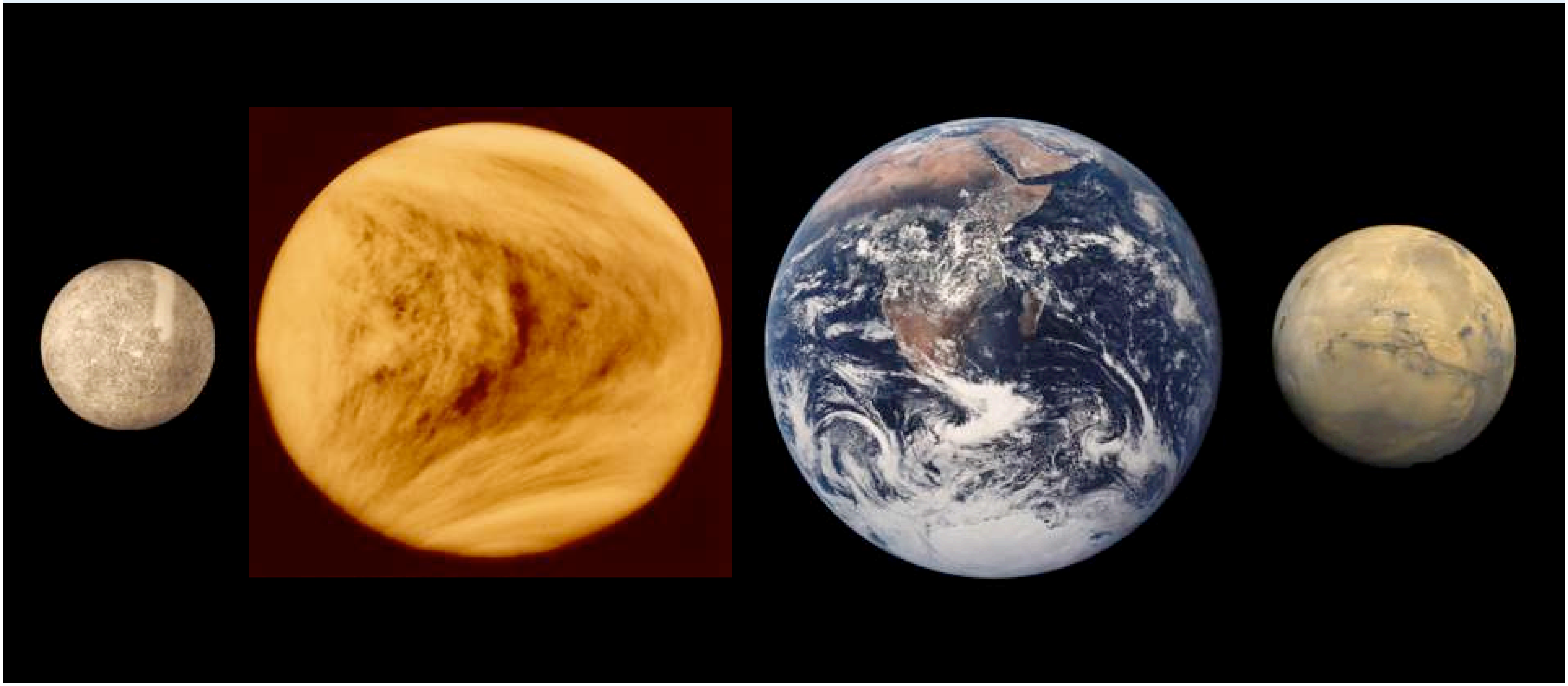
Venus: Earth's near-twin

Rocky planets- size comparison



Mercury Venus Earth Mars

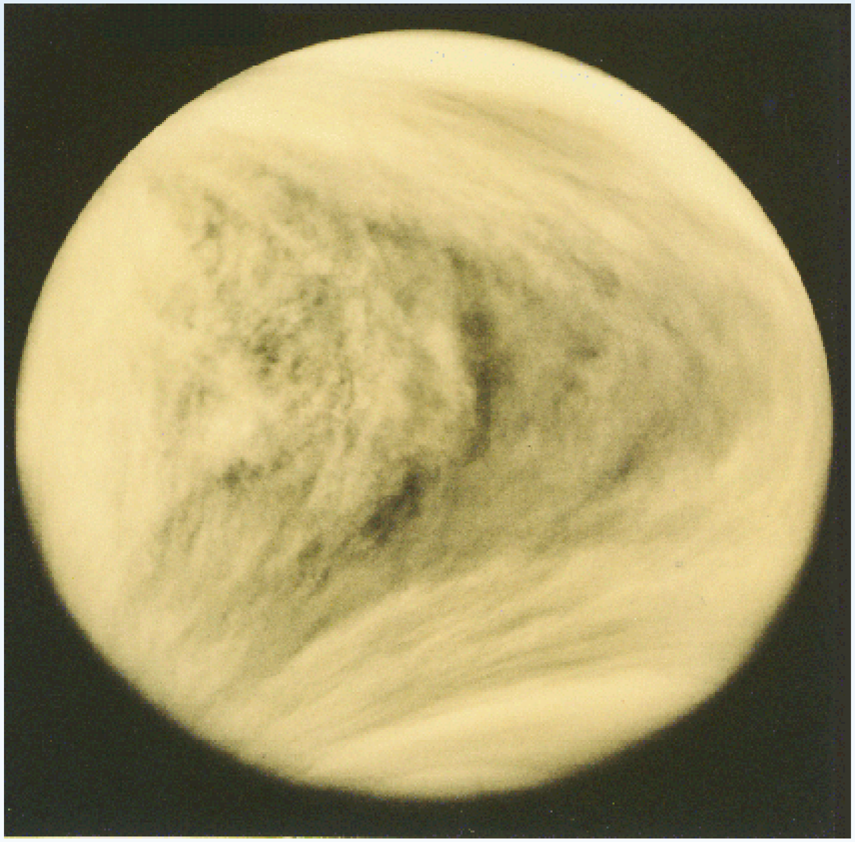
Venus: A Challenge for Exploration

- Solar day 117 days
- Surface temperature 452 C (850F)

  •Tops of mountains are slightly cooler: at the top of Maxwell Montes (10.4 km above mean elevation), temperature is “only” 390 C (725 F)

- Surface pressure 92 bars (equals pressure 1-km under the ocean) carbon dioxide

•Clouds are concentrated sulfuric acid droplets

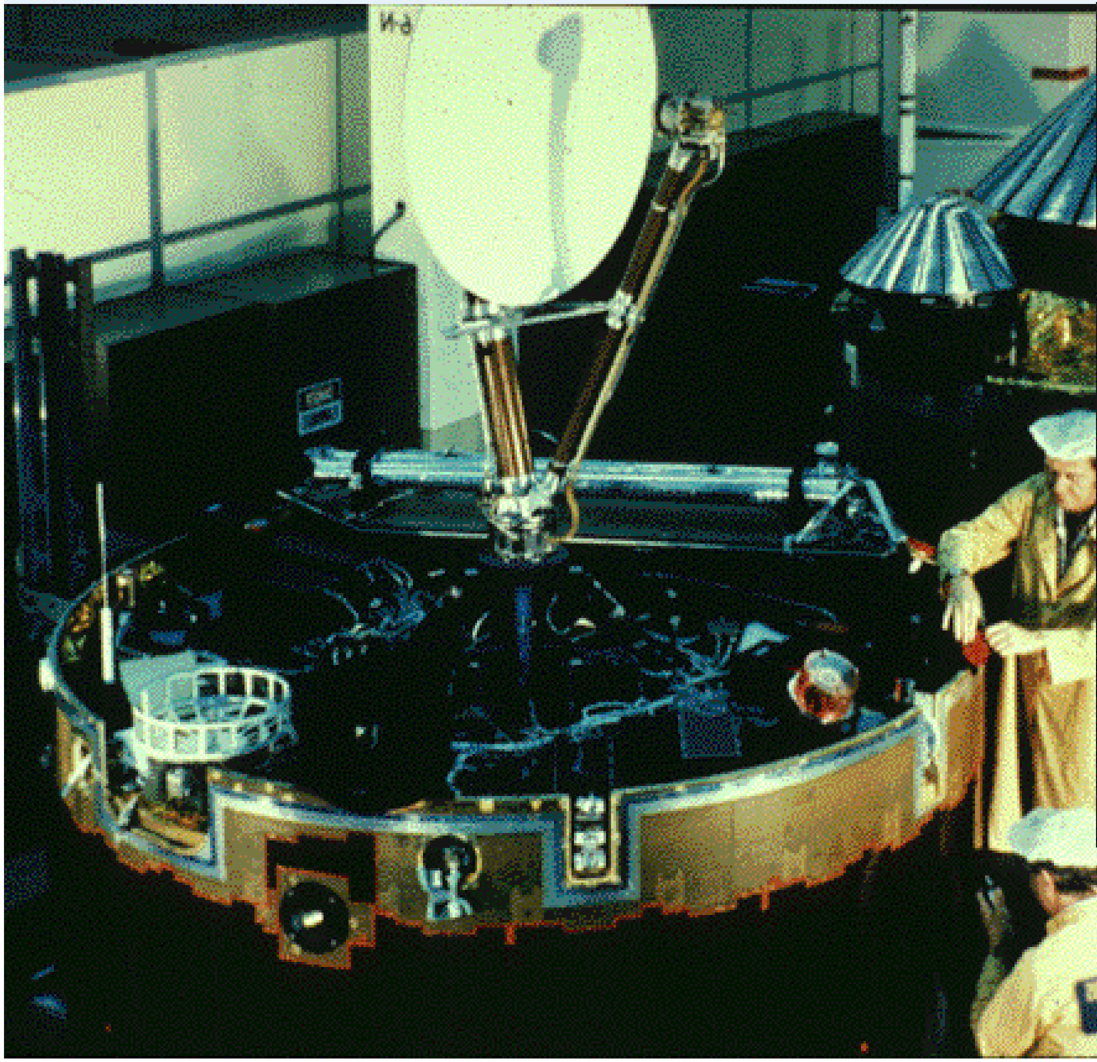


Venus in the UV (viewed from the Pioneer Venus orbiter)

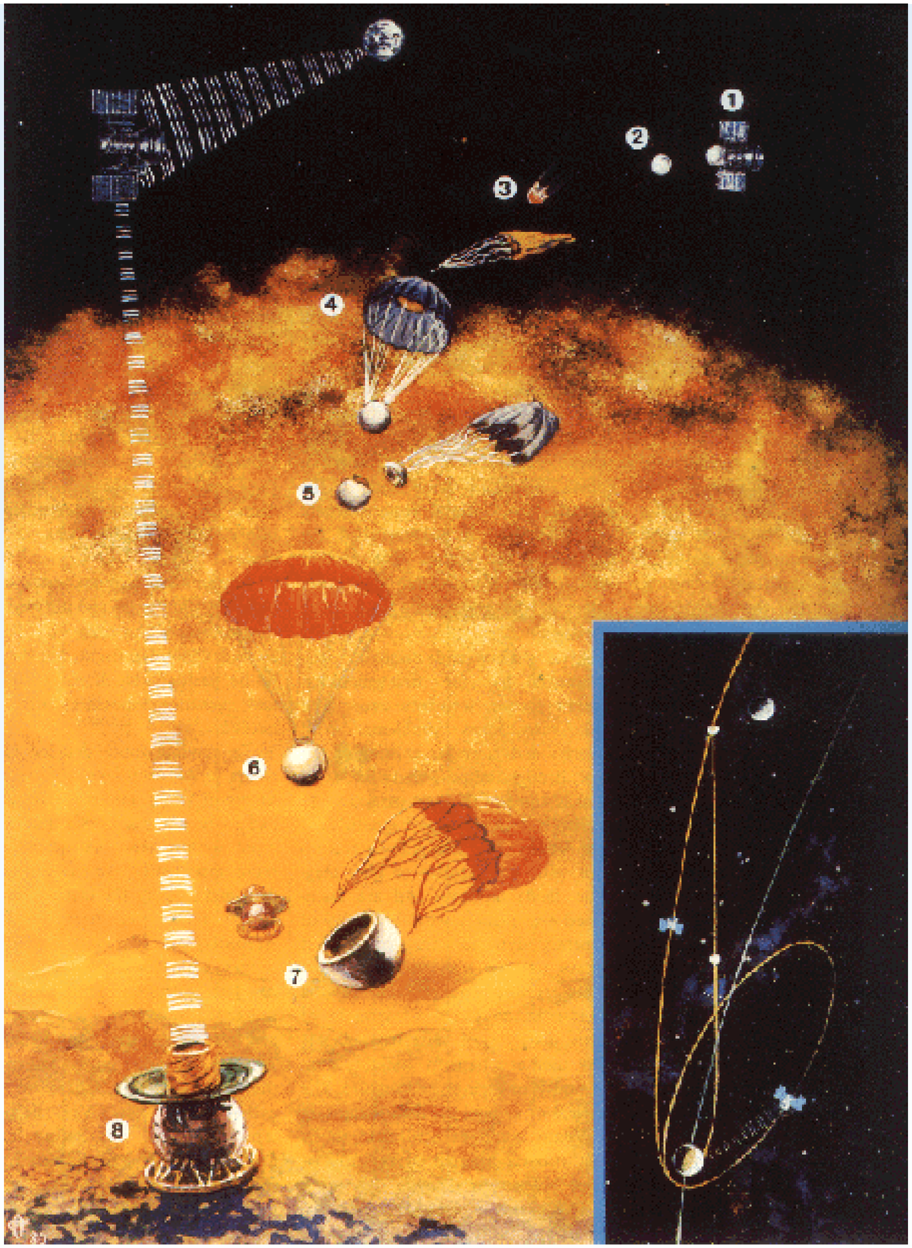
Venus Exploration is a tough challenge!

Previous missions: Pioneer Venus (NASA)

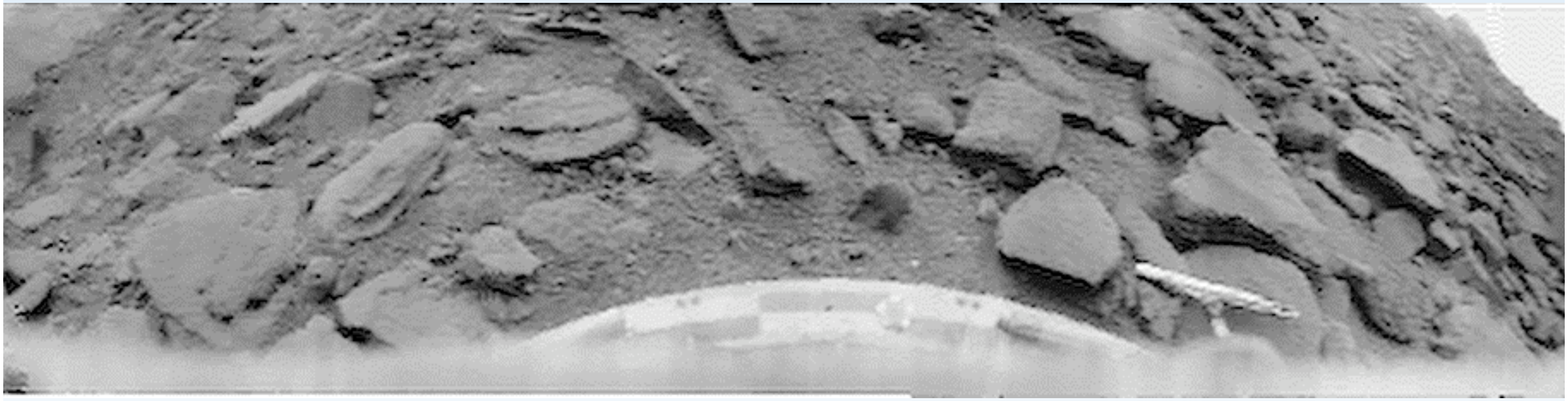
- Pioneer Venus mission: four atmospheric probes plus orbiter (1978)



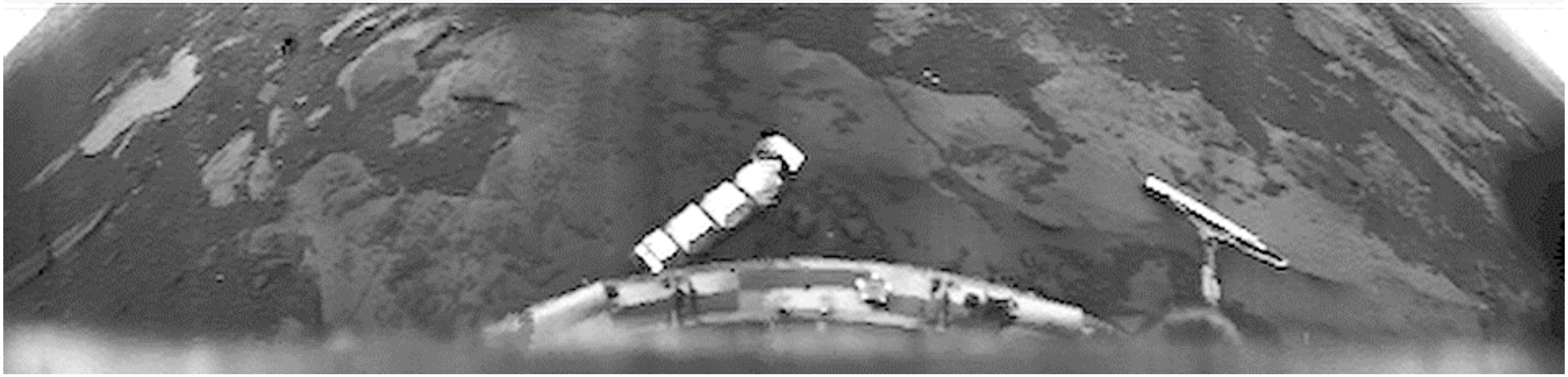
Previous Missions: Venera (Russian)



The Surface of Venus
First pictures from the surface from Russian “Venera” landers



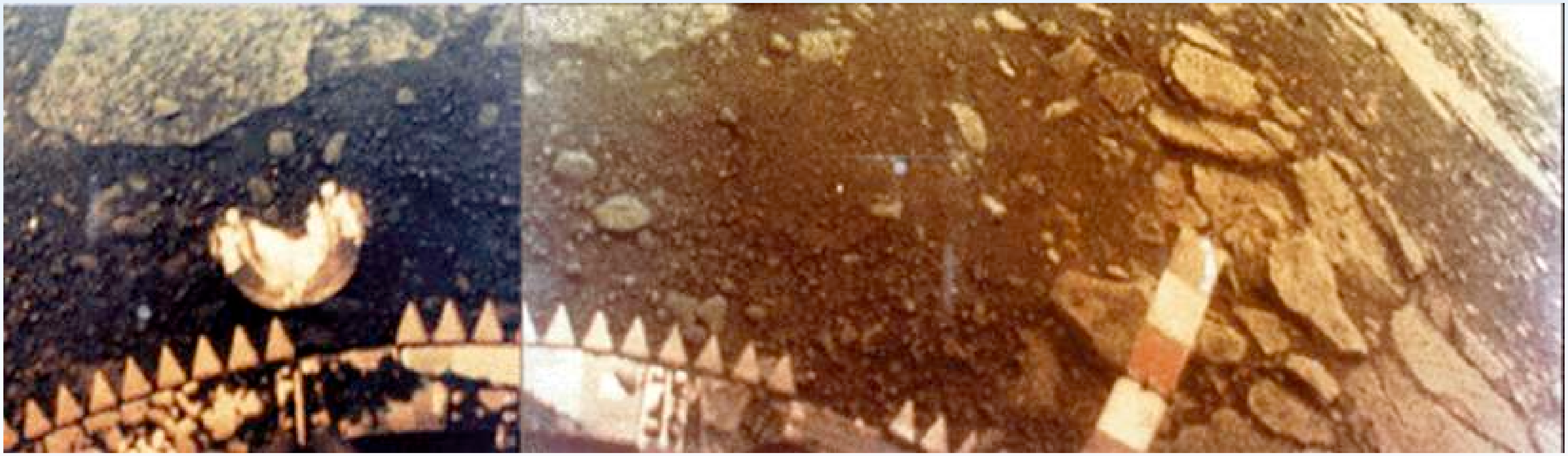
Venera-9 image



Venera-10 image

Venera-14 images

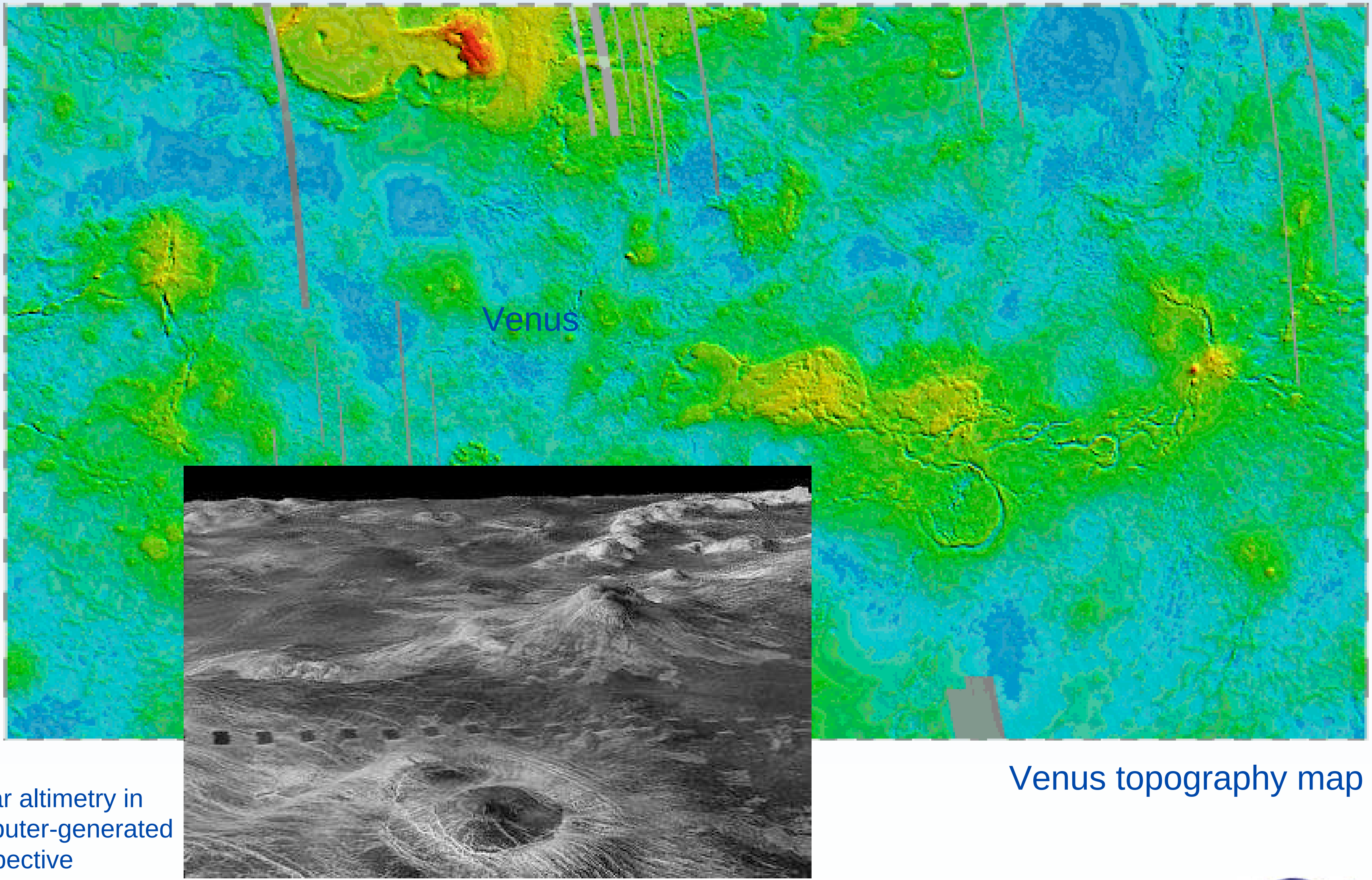
The Surface of Venus
seen from the Russian “Venera” Venus landers



Venera-13 image

•Venera probes survived on surface for under 2 hours before failure

Previous Missions: Magellan orbital Radar (NASA)



Venus topography map

Radar altimetry in computer-generated perspective

Previous Missions: VEGA (Russia):

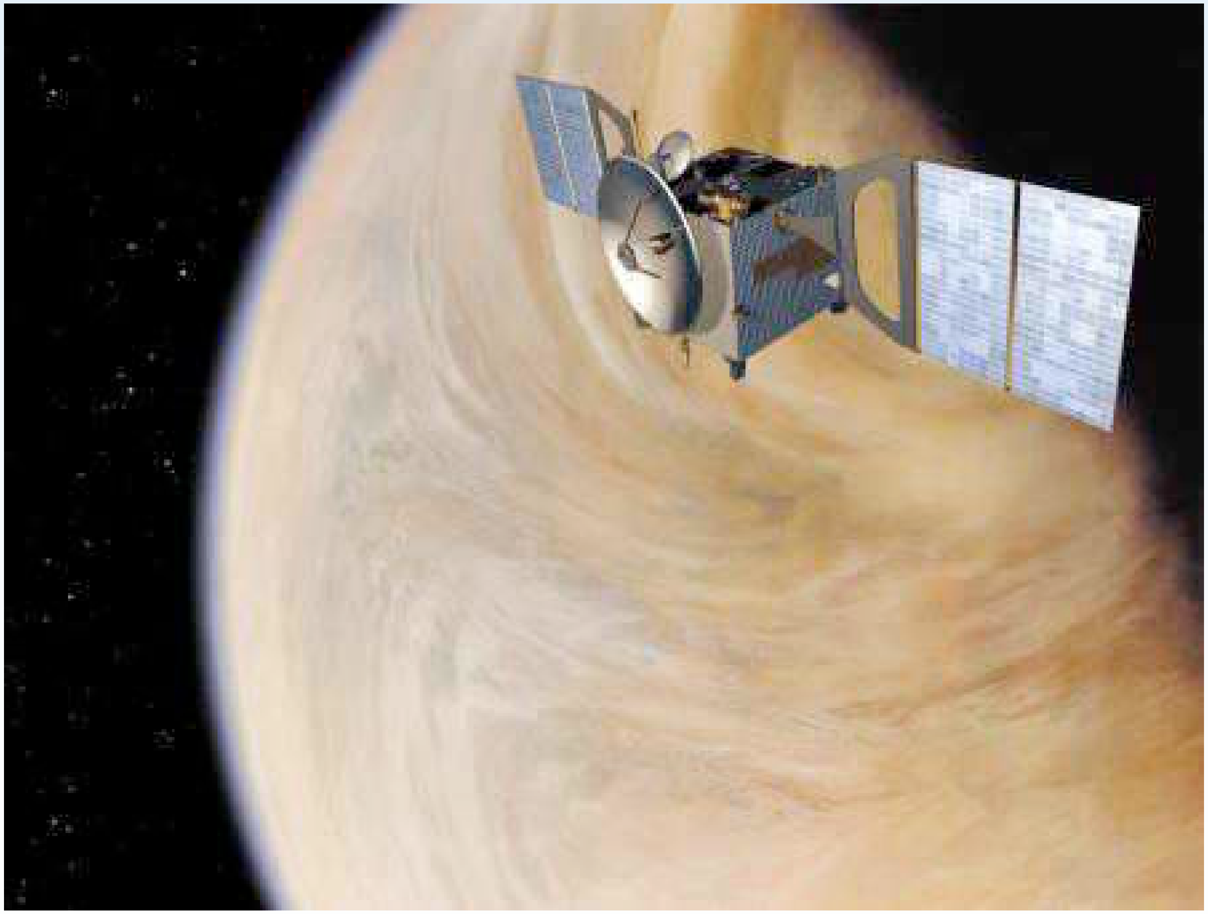
ballooning in the Venus atmosphere

2 balloons floated for 48 hours at 54 km altitude
delivered by Halley's comet probe during Venus swingby

Russian VEGA balloon

ESA “Venus Express” orbiter

arrived in Venus orbit 2006



Future Venus Exploration?

- **Atmospheric exploration**
- **Surface exploration**
- **Venus surface sample return**

Goal: **Science Driven Exploration**
Science Questions: ***Geology***

- What process resurfaced the planet in the (geologically recent) past?
- Why doesn't Venus have plate tectonics like Earth?
- Does Venus have active volcanoes?
- Is the interior of Venus similar to the Earth?
- What is the "snow" deposits on the top of Venusian mountains?
- How does the sulfur in the atmosphere interact with the rock?

Goal: **Science Driven Exploration**

*Science questions: **Atmosphere and Climate***

- Venus is the **greenhouse planet**: understanding the climate of Venus will teach us about the (past and future) climate of the Earth
- Understand planetary atmospheres by the process of comparison
- What causes the atmospheric super-rotation?
- What are the aerosol particles?
- What was Venus like in the early solar system? How did it lose its hydrogen?

Goal: **Science-driven Exploration**

Science Questions: Astrobiology

- Did Venus ever have an ocean? Did it once have life?
- What is the history of the chemical evolution of the Venus atmosphere? What can it tell us about the possibility of life starting on earthlike planets?
- Atmosphere of Venus has unexplained deviations from equilibrium: could this be signs of present day life?

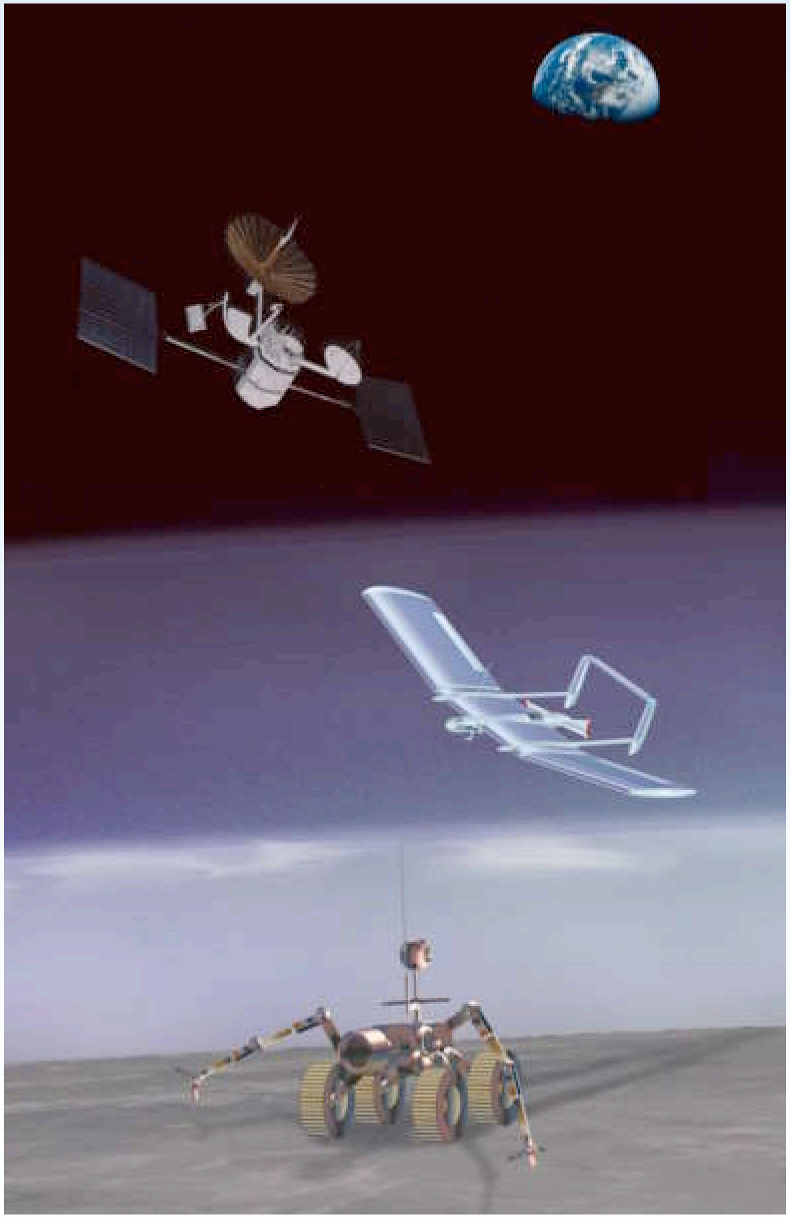
  (ref: Grinspoon 1997; Sattler *et al* 2001, Schulze-Makuch 2002)

Mission Goal:
Exploring Venus from the surface and the atmosphere

cool upper atmosphere

hot lower atmosphere

very hot surface



Venus Surface Exploration is highly challenging

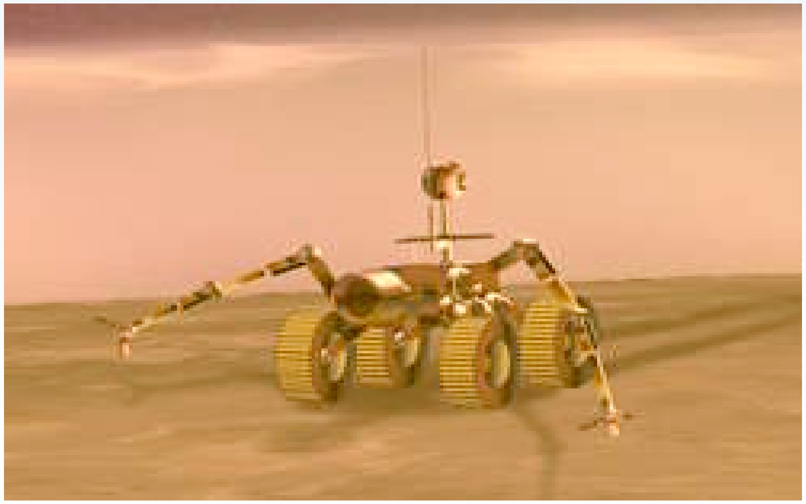
- Russian Venera probes lasted less than two hours on the surface of Venus
- One American Pioneer probe made it to the surface and survived about an hour
- Extremely hostile environment!

but

- Scientifically interesting environment

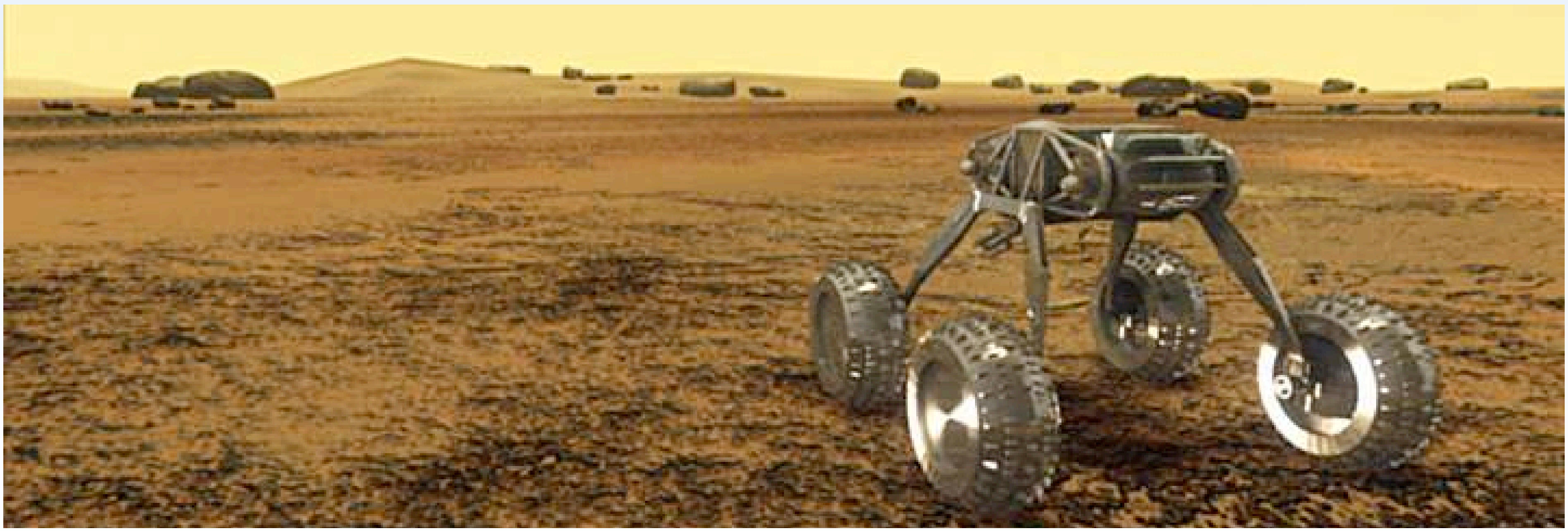
Venus Surface Exploration: New Technology Required

- Electronics needed to operate at 450+ C
- Computers needed to operate 450+ C
- Power System needed to operate at 450+ C
- Mechanical components to operate at 450+ C



Science mission for Venus Surface Rover

- Characterize the surface at geologically diverse locations
- emplace seismometers to determine the interior structure



Venus Surface Rover

The surface mission is to characterize the surface of Venus at a level of detail comparable to that of the Mars Exploration Rovers (MER) mission.

Mission criteria:

1. Mission duration on surface: 50 (Earth) days.
2. Mobility requirement: 600 meters minimum.
3. Multiple landing sites with geological diversity.

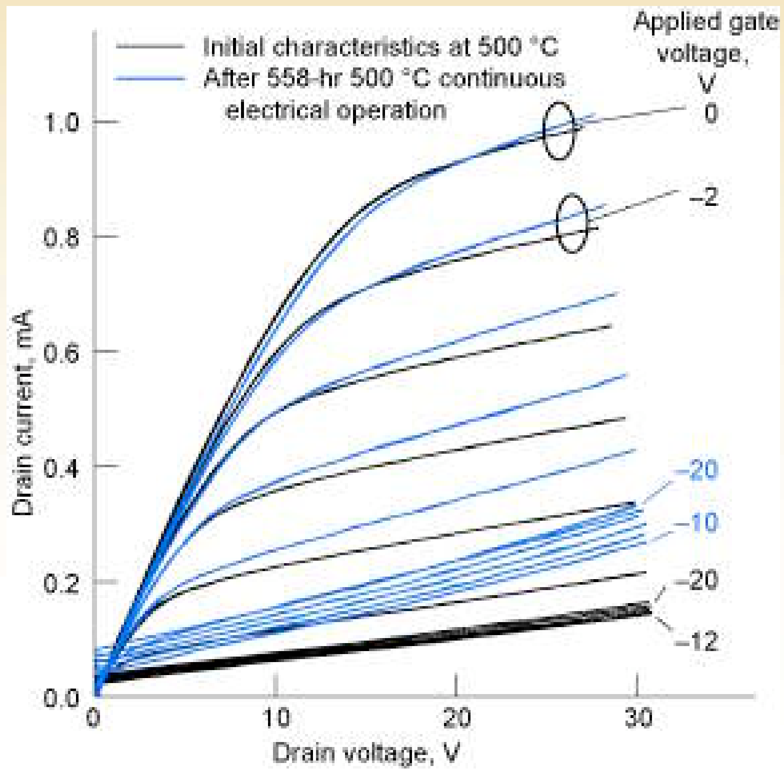
The science mission of the Venus surface rovers is to examine the surface at the local scale, measuring the chemistry and diversity of rocks and determining the interaction of the atmospheric chemistry with the rock mineralogy. The rover also emplace multiple seismometers to determine the interior structure of Venus, answer the thick crust/thin crust model question, and search for present-day tectonic activity and volcanism.

Electronics for surface operation: trade-off study

- **Approach 1**: Rover electronics capable of operating at surface temperature of 460C
  - 460C electronics is being developed, based on SiC material

Electronics for surface operation: trade-off study

- 500°C electronics being developed, based on SiC
  - •Transistors demonstrated to operate at 500 C
  - •SiC transistors have been made and operated at Venus temperatures
  - •Thousands of hours at temperature now demonstrated
  - •First integrated circuit: SiC op amp
  - •Demo radio receiver in progress
  - •Cameras and sensors: more difficult, but could be constructed (conceptual camera design uses scanned GaP photodiodes)



•Reference: Phil Neudeck, NASA Glenn *Research & Technology 2005*, NASA/TM-2006-214096

•http://www.grc.nasa.gov/WWW/RT/2005/RI/RIS-neudeck2.html

Electronics - paper

Electrical Operation of 6H-SiC MESFET at 500 °C for 500 Hours in Air Ambient

David Spry[1], Philip Neudeck[2], Robert Okojie[2], Liang-Yu Chen[1],
Glenn Beheim[2], Roger Meredith[2], Wolfgang Mueller[3], and Terry Ferrier[2]

[1]OAI, Cleveland, OH
[2]NASA Glenn Research Center, Cleveland, OH
[3]Research 2000, Inc. Cleveland, OH

Abstract

A high temperature n-channel 6H-SiC metal semiconductor field effect transistor (MESFET) was fabricated, packaged, and electrically operated continuously at 500 °C for over 500 hours in an air ambient with less than 10% change in operational transistor parameters. To the best of our knowledge, this is the first report of a semiconductor transistor operating in this harsh environment with excellent stability over an extended period of time. The fabrication process that enabled such stability in air atmosphere featured multiple levels of high temperature metal and dielectric passivation to prevent contamination (particularly oxygen) from reaching electrically sensitive interfaces. A thick-film metallization based ceramic package with conductive die attach material and Au wire bonds facilitated long-term testing under electrical bias at 500 °C. Over the course of the 500 hour operational test in air, the only observed degradation of transistor characteristics was increased leakage of the gate-channel diode as anneal time increased. This demonstration of 500 °C transistor durability represents an important step toward significantly expanding the operational envelope of sensor signal processing electronics for harsh combustion-engine environments.

Electronics for surface operation: trade-off study

- **Approach 1**: Rover electronics capable of operating at surface temperature of 460C
  - 460C electronics is being developed, based on SiC materials
- Microprocessor: highest-temperature existing microprocessor operates at 300C
- **Microelectronics for Venus Surface Conditions not yet ready**

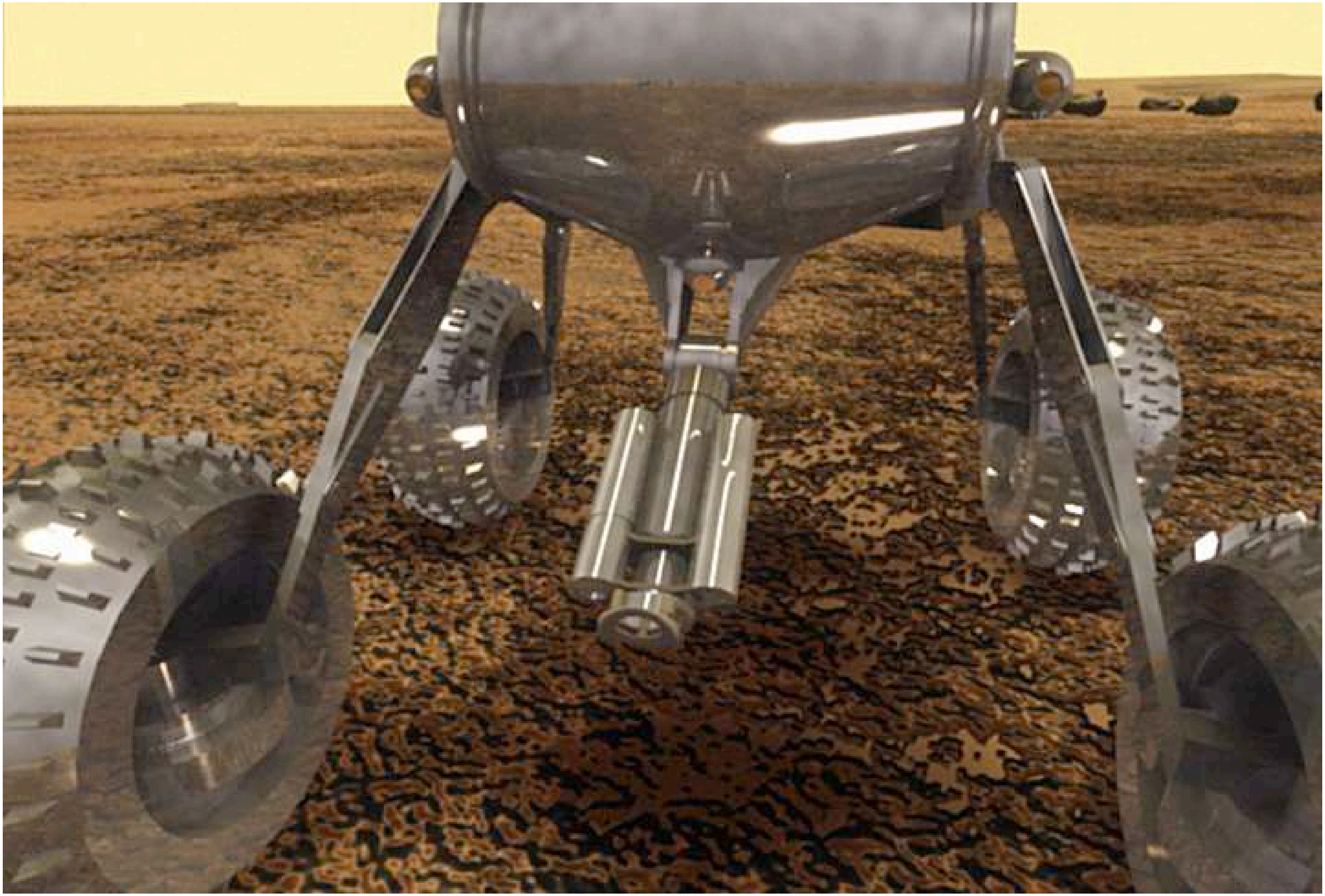
–Conclusion:

–Some parts are ready, but whole mission cannot be done with available parts

–Integrated circuits and computers are farther in the future

Electronics for surface operation: trade-off study

- Approach 1: Rover electronics capable of operating at surface temperature of 460C
  - 460C electronics is being developed
  - Not available today
  - Integrated circuits and computers are farther in the future
- **Approach 2:** Refrigerator to keep electronics at low temperature
  - Requires power and moving parts
  - Allows existing electronics



Microcontroller data sheet

Honeywell

HTMOS™ High Temperature Products *Preliminary*

HIGH TEMPERATURE 83C51 MICROCONTROLLER

HT83C51

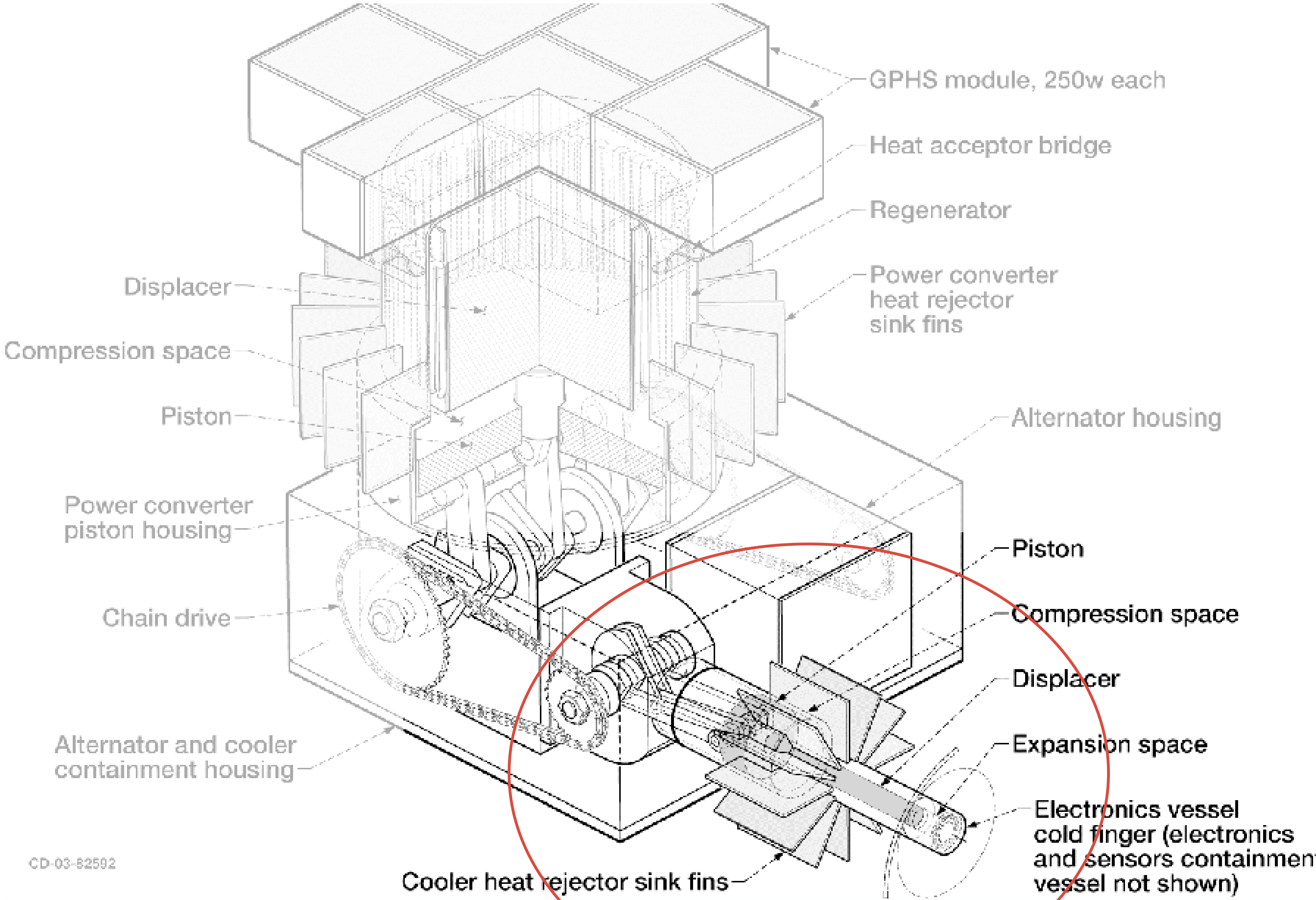
FEATURES

- HTMOS Specified Over -55 to +225°C
- 8-bit CPU Optimized For 5 Volt Control Applications
- Hermetic 40-Pin Ceramic DIP
- 64K External Data Memory Address Space

These microcontrollers provide guaranteed performance supporting operating frequencies in excess of 16 MHz over the full -55 to +225°C temperature range. Typically, parts will operate up to +300°C for a year, with derated performance. All parts are burned in at 250°C to eliminate infant mortality.

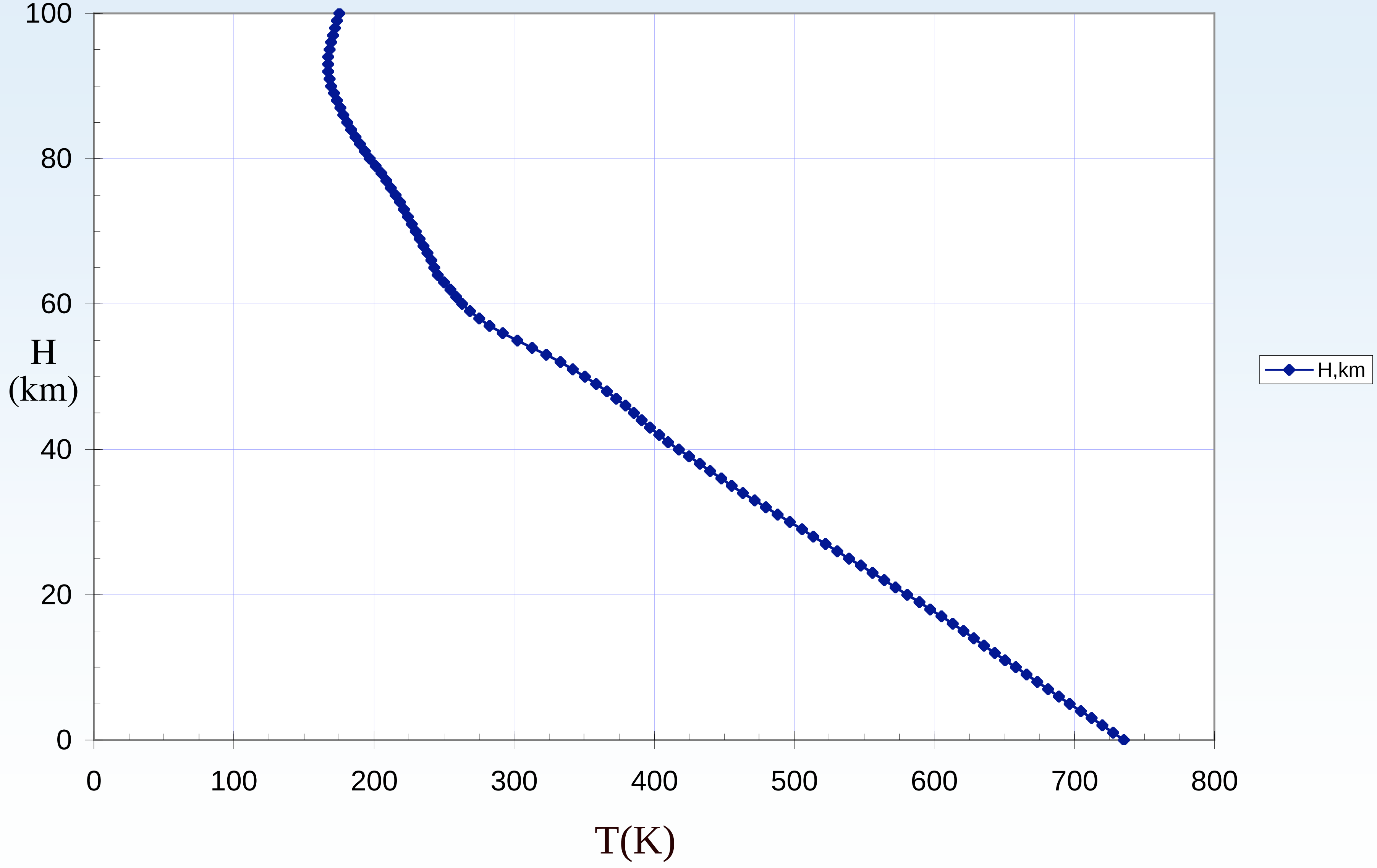
Venus Surface cooling system

Parameter	Value
Type	Stirling cycle
Stages	1
Heat sink temperature	500 C
Cold temperature	200C
Heat transferred	105.7 W
Heat rejected	344.6 W
Overall coefficient of performance	37.6%
Mass	1.6 kg



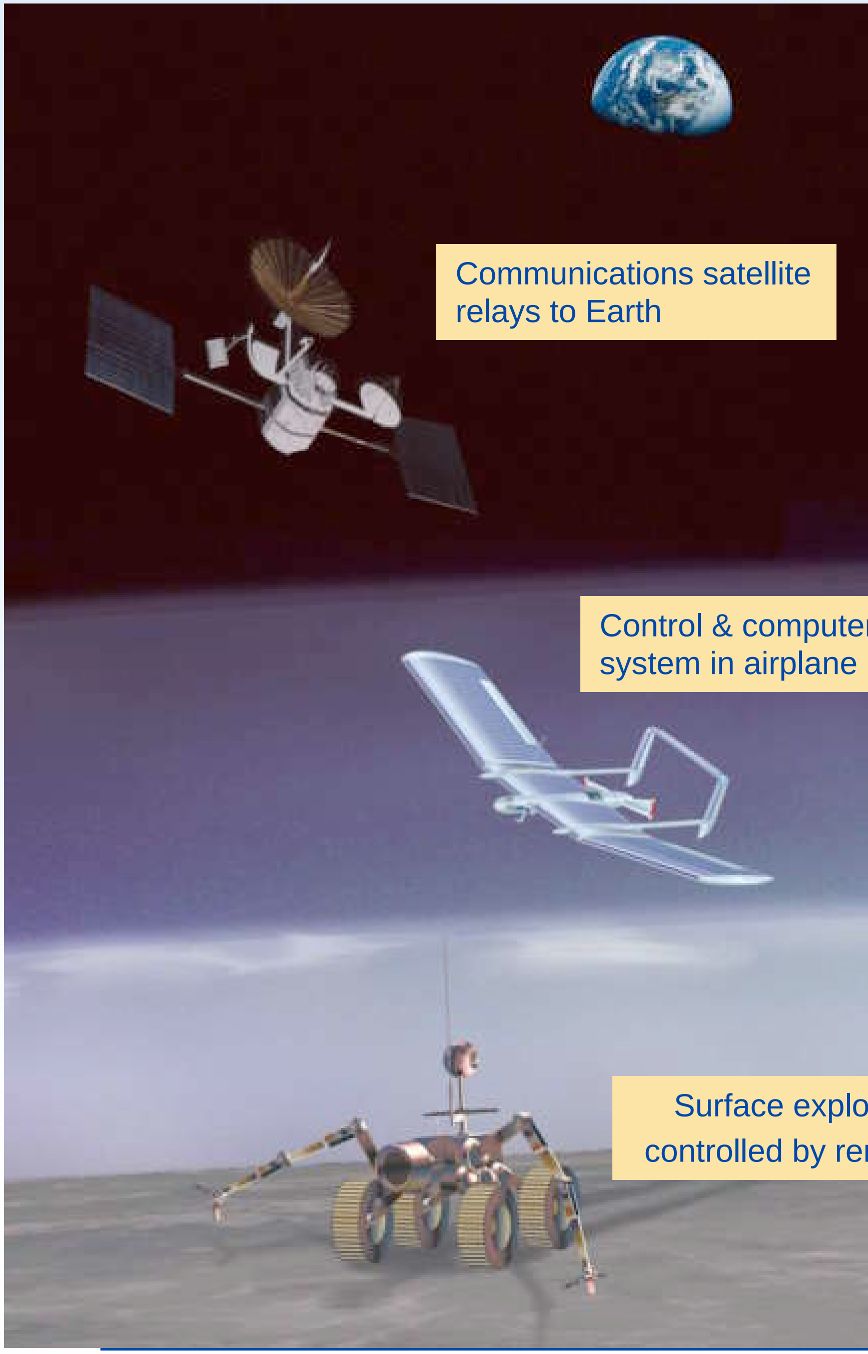
Sterling cooler design

Atmospheric temperature decreases with altitude



Electronics for surface operation: trade-off study

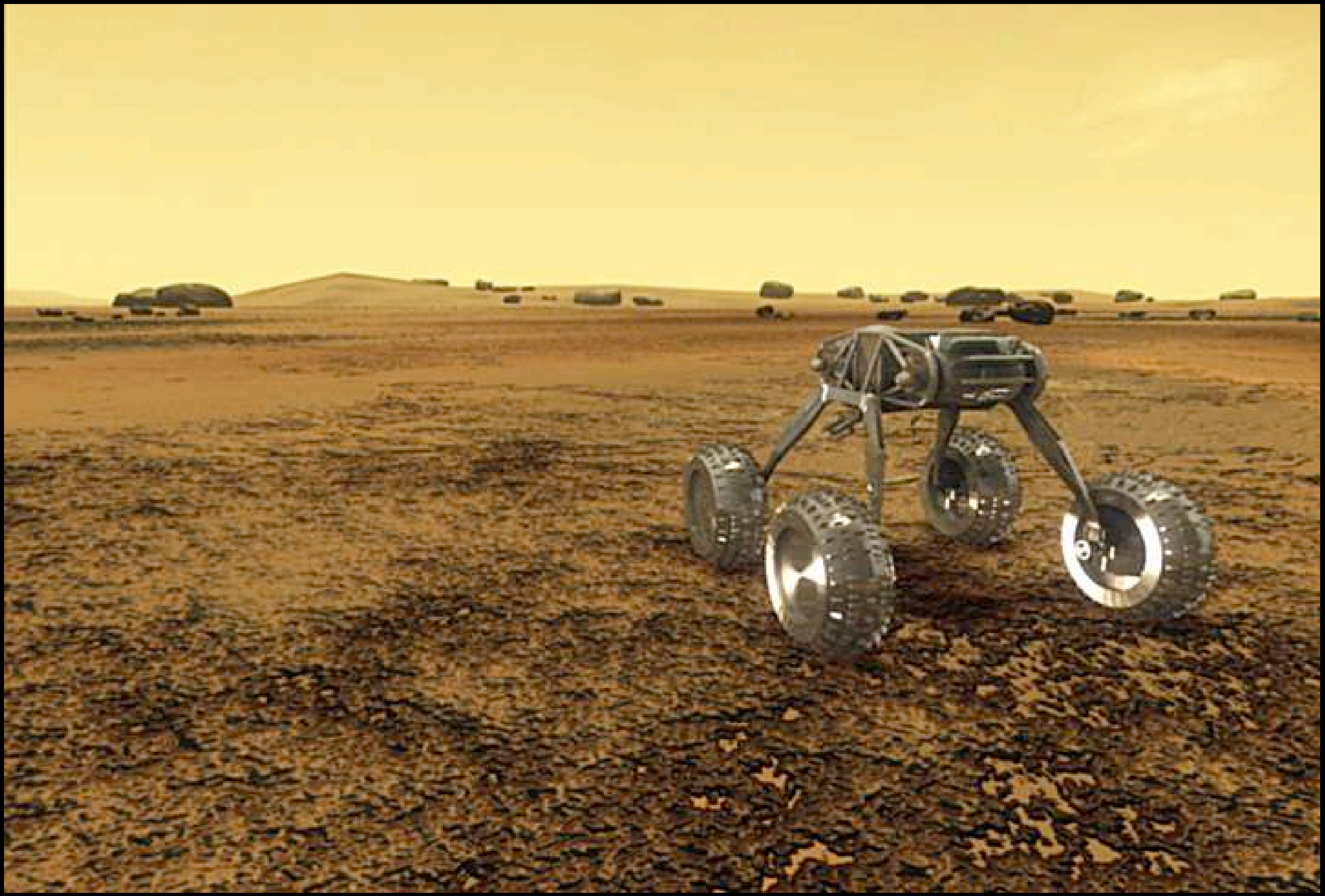
- Approach 1: Rover electronics capable of operating at surface temperature of 460C
  - 460C electronics is being developed
  - Not available today
  - Integrated circuits and computers are farther in the future
- Approach 2: Refrigerator to keep electronics at low temperature
  - Requires power and moving parts
  - Allows existing electronics
- **Approach 3:** Some rover electronics operating at 460C, but computer is overhead in cooler atmosphere
  - More complicated
  - Allows use of electronics available today



Robotic Exploration Concept:

"brains" of the robot stay in the cool middle atmosphere

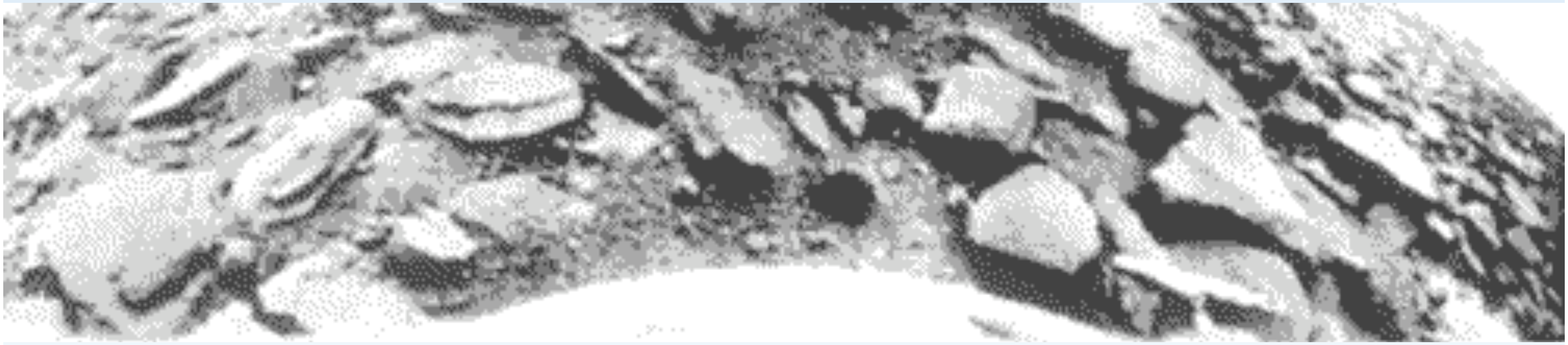
- Computer stays in cooler middle atmosphere
- Surface robot uses simple high-temperature electronics
- Aerostat vs. airplane trade study indicates airplane is preferable



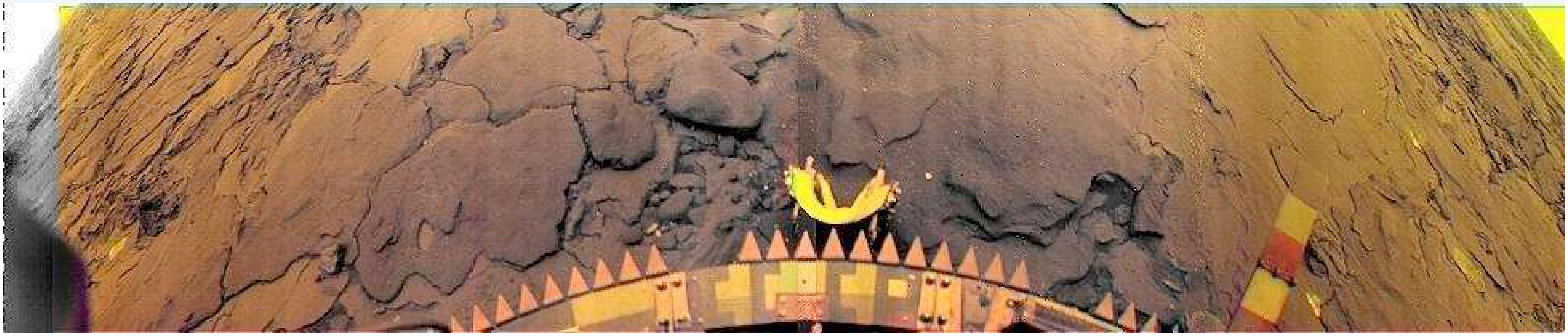
Animation is available at:

http://www.grc.nasa.gov/WWW/5000/pep/photo-space/venus-mission-design.htm

Venus surface

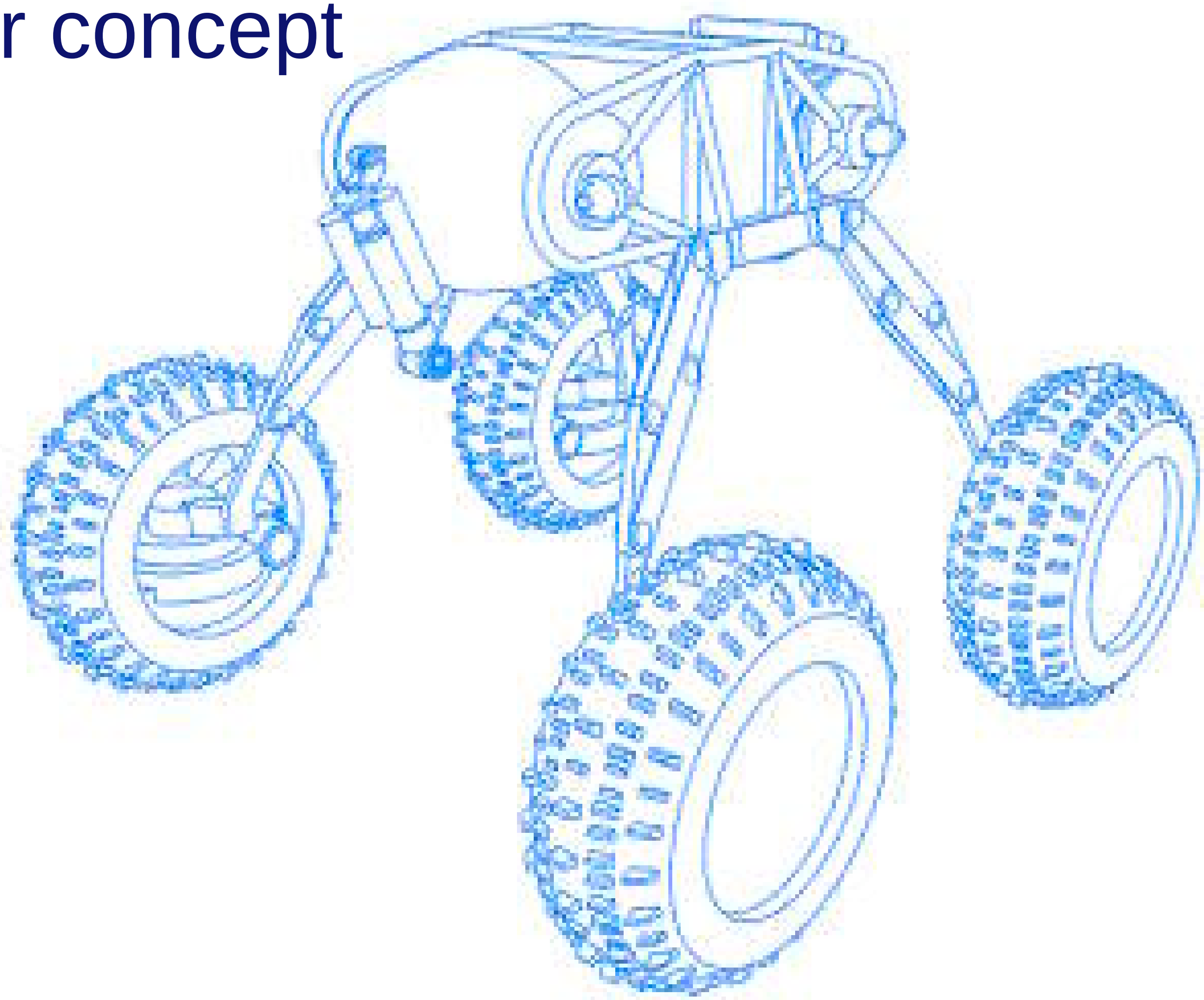


•Venera 9: The size of most rocks was estimated to be around 50-70 centimeters and the height 15-20 centimeters.



•Venera 14: landing site was a smooth plain

Rover concept



Rover landing concept

•Rover lands directly on parachute-- after the aeroshell is jettisoned, there is no separate "lander" vehicle

•High temperature parachute material such as glass-fiber cloth is required

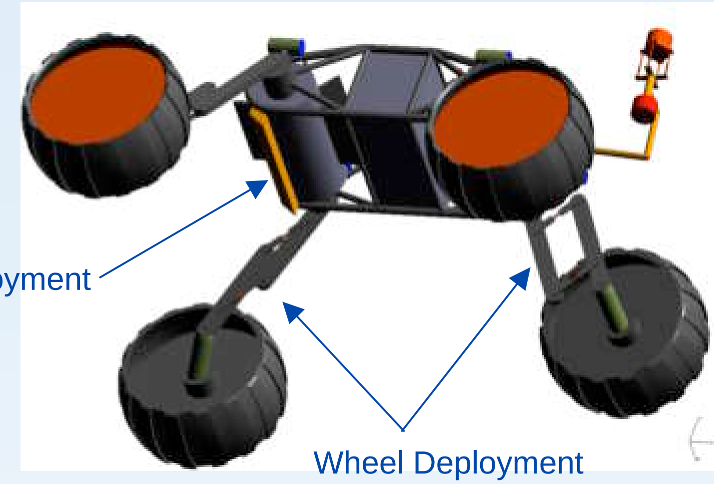
•Due to thick atmosphere, parachute descent velocity is low (12 x less than parachute descent velocity on Earth)

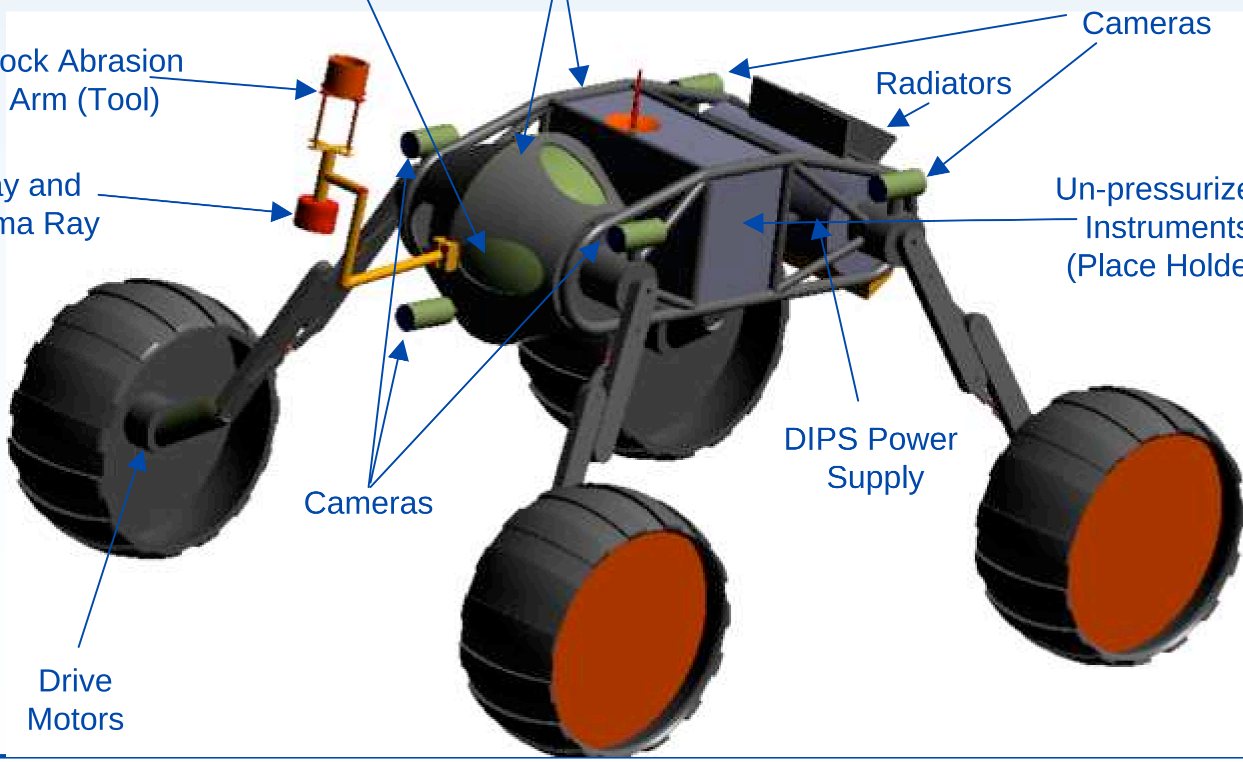
- •Vehicle will sense transverse velocity relative to surface and rotate so that velocity is in direction of wheel rotation

  (note that surface winds are low)

•"Land on Wheels" technique is now baselined for 2009 MSR Mars rover, with similar vertical velocities.

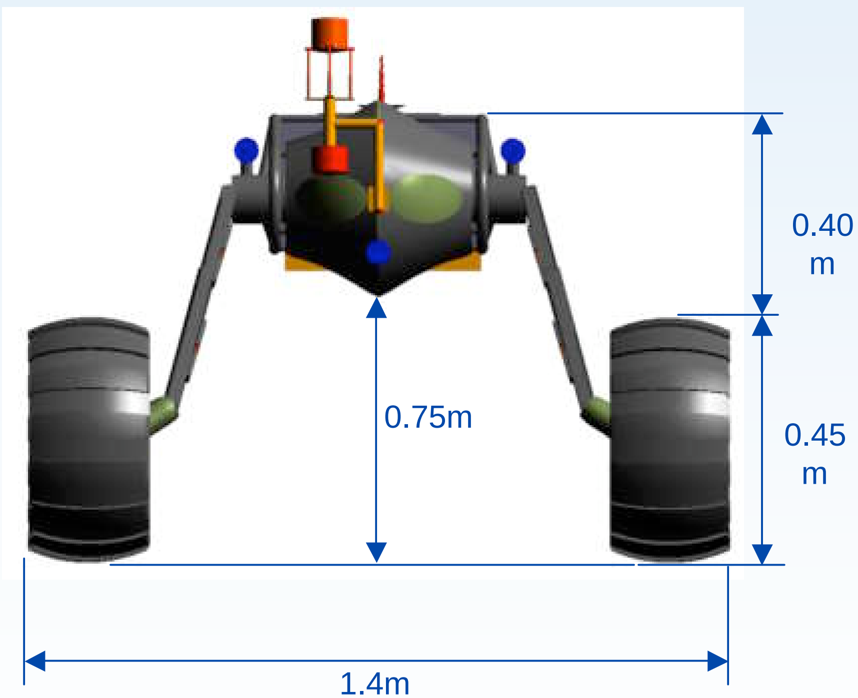
Surface Rover concept

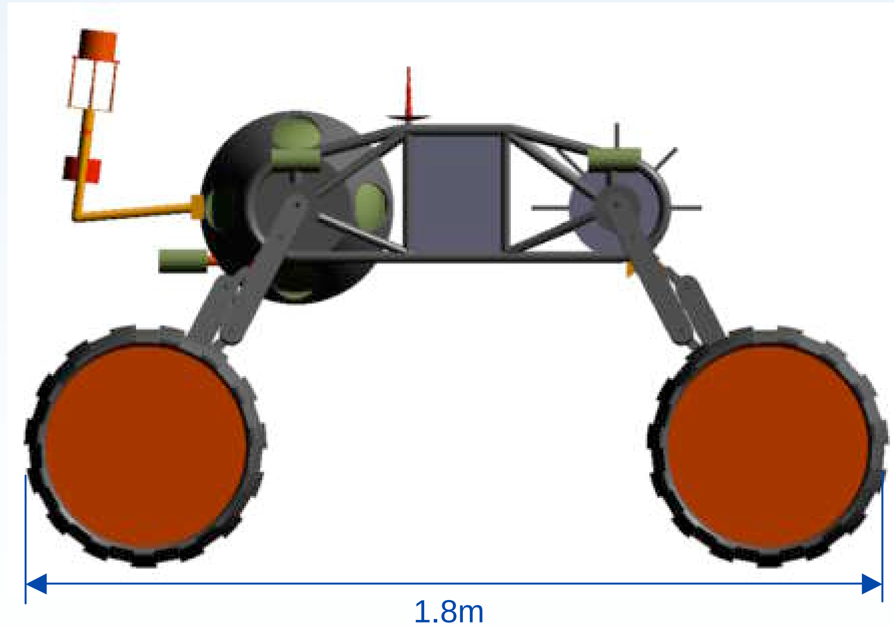




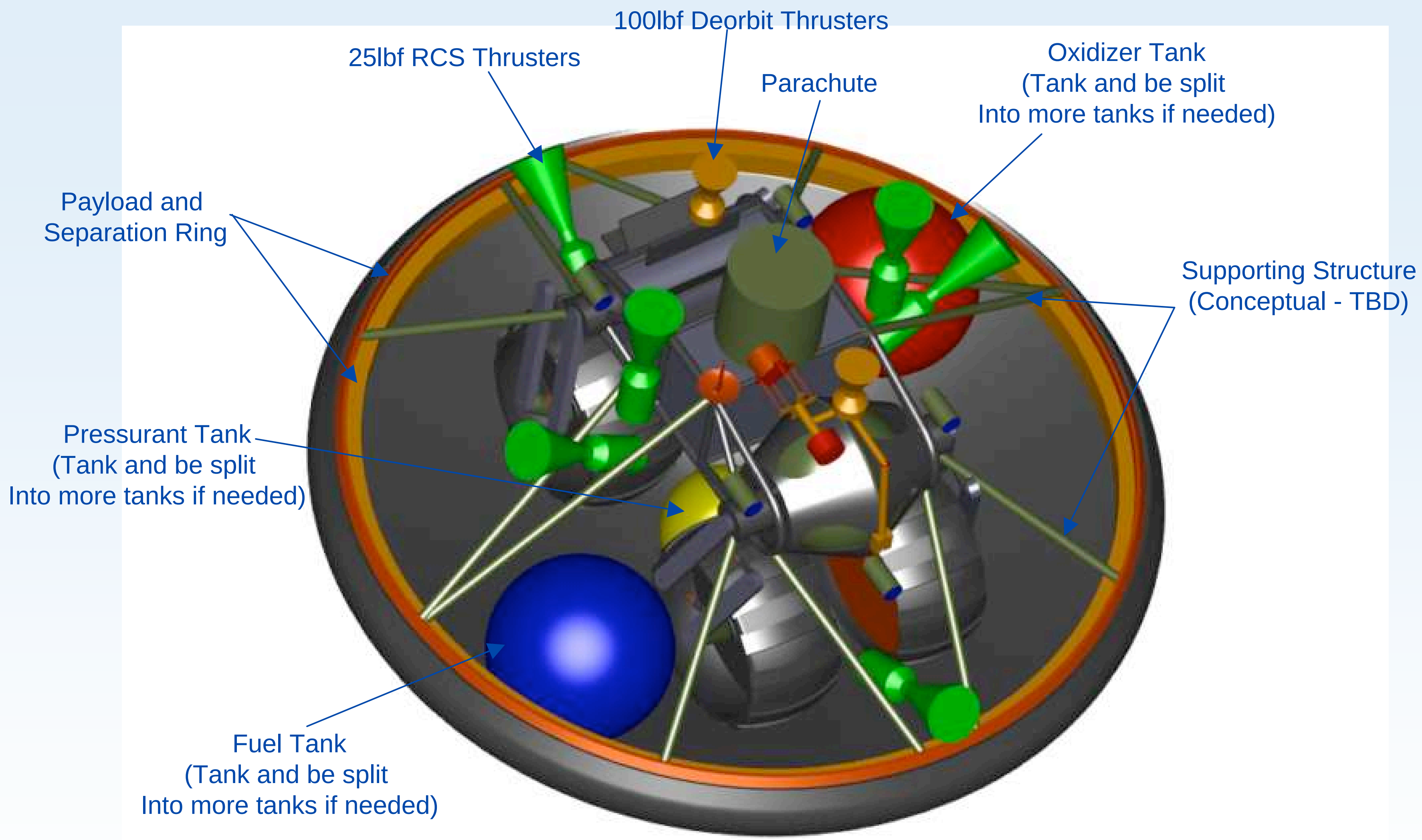
CAD model by
Shawn Krizan,
NASA LaRC

Surface Rover dimensions





•CAD model by Shawn Krizan, NASA LaRC



Venus Rover packaged into aeroshell

Max Aeroshell Diameter = 2.0m

Venus Surface Robot Technologies: motors and actuators

High temperature motors/actuators

Motor or actuator	Max operating temperature (C)	status
Baker Hughes GeoThermal	160	commercial
Swagelock pneumatic	200	commercial
Rockwell Scientific SiC	200	development project
NASA Glenn R&T high-temperature actuator	400 600	prototype goal research target
NASA Glenn switched-reluctance motor	540	demonstrated; 8000 RPM, 27 hours
U. Sheffield Linear actuator	800	technology demonstrator: 1 mm throw, 500N force
NASA Glenn/MSU RAC smart materials: Shape memory alloy actuators	150 500 1000	Shape memory (SMA): commercial SMA: material demonstrated SMA: high temperature goal
NASA Glenn smart materials: piezoelectric	>1000	Piezoelectric high temperature goal

Switched-reluctance motor capable of operation at 540 C

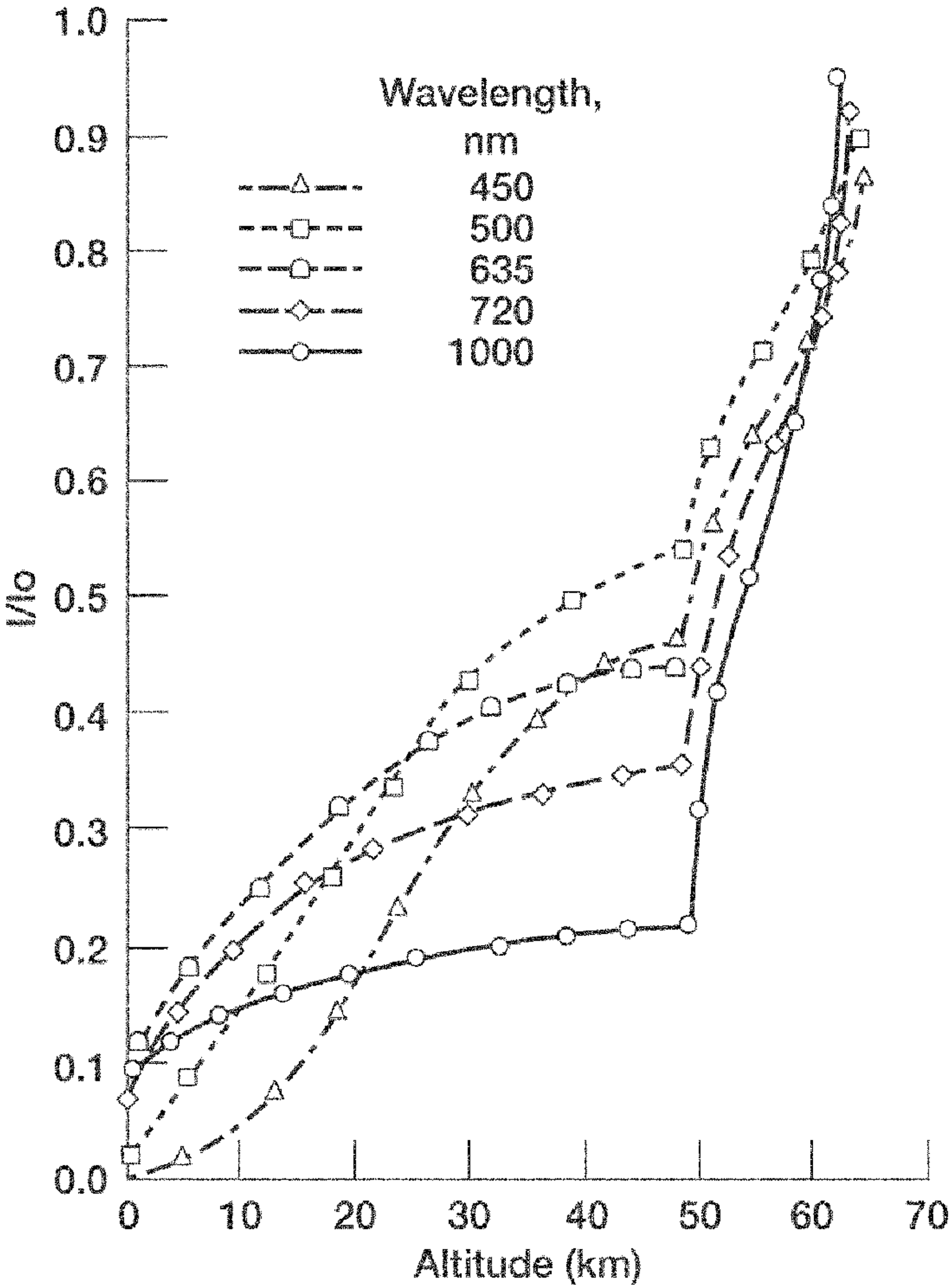
•Small version of this motor has now been demonstrated at Honeybee robotics

Power source

- *Approach 1*: Radioisotope Power source
- *Approach 2:* Solar power
- *Approach 3:* microwave beamed power
- *Approach 4:* Chemical energy conversion

Venus Surface power source

- *Approach 2:* Solar power
  - Low light levels and high temperature at surface
    - Existing solar cells work poorly at high temperature
    - New high-temperature solar technologies are most sensitive to blue light
  - Good solution for high-altitude aircraft (>50km)
  - High temperature solar-cell technology is improving
  - Approach not feasible on surface with today's technology



Solar energy in the Venus atmosphere

- At surface, power available is 10% of exoatmospheric power at 1000 nm, <1% at 450 nm

Venus Surface power source

- *Approach 3:* microwave beamed power
  - Station in atmosphere produces solar power; power beamed to surface by microwaves
  - Many technical questions need to be answered
  - Used as backup approach

Venus Surface power source

- *Approach 4:* Chemical power
- Battery or fuel cell
  - Good for prime power for short mission
  - For long mission, storage of reactants needed becomes critical
  - Analyzed for power buffering for isotope power systems

Venus Surface power source selected

- *Approach 1*: Radioisotope Power source
  - Although 460 C is a higher heat rejection temperature than most dynamic conversion approaches, should be possible
  - Long history in planetary exploration
  - Dynamic or thermoelectric conversion approaches possible
  - **Baseline technology chosen for the Venus rover**

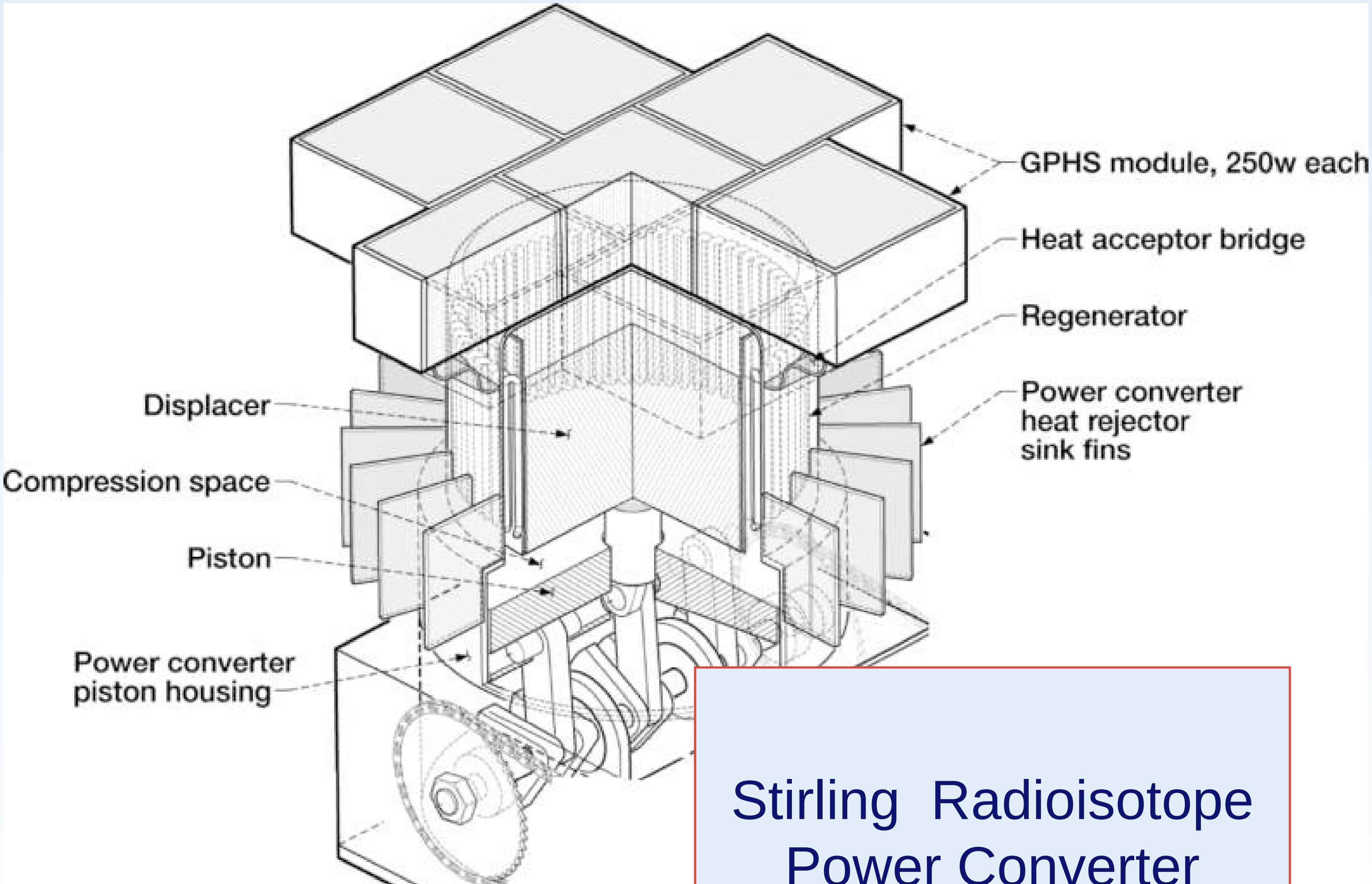
Radioisotope power: thermoelectric conversion

Parameter	Value
Type	thermoelectric
Power produced	30 Watts
T (source)	1077 C
T (sink_	600C
Conv. efficiency	5%
Input Qh	594 W
Heat Rejected, Qr	564 W

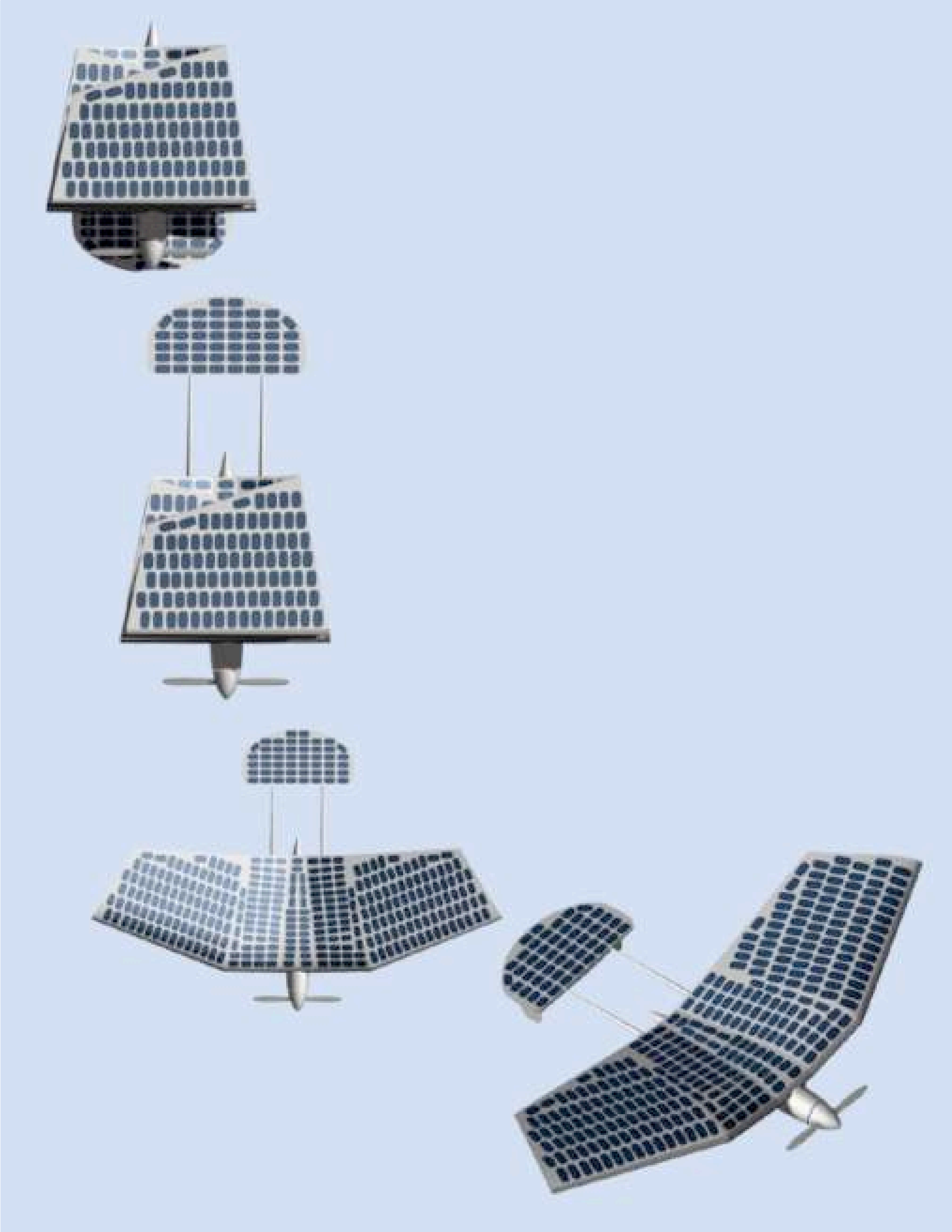
- thermoelectric converters similar to Cassini power system
- Advantage: no generator needed; high TRL
- Radiator area .075 square meters
- Possible approach for small power system
- Three units would be needed for 100 watts usable power

Radioisotope Power: Sterling conversion

Parameter	Value
Type	Stirling cycle
Power output	478W
Source	7 250-W GPHS units
T (source)	1200 C
T (sink)	500C
Heat input	1740 W
Heat rejected	1267 W
Overall efficiency	23.4%
Mass	21.6 kg



Stirling Radioisotope Power Converter



Venus airplane unfolding

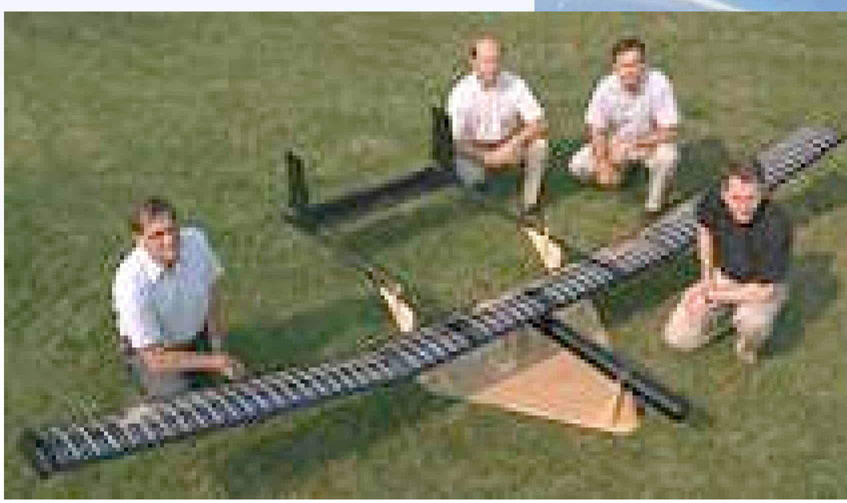
Solar Airplane Figure of Merit

- 50-60 km above surface, Venus atmosphere density profile similar to Earth's
  - Airplane design can use Earth experience
- Gravity 90% of Earth's
  - Powered flight easier
- Above the clouds, Venus has more sunlight than Earth
  - **Solar flight is easier on Venus than on Earth**
- Acid droplets in atmosphere require all exposed surfaces be corrosion resistant
  - Avoid exposed metal surfaces.
  - All metal surfaces need passivation coating
  - Acid-resistant materials are well developed technology

Solar airplanes on Earth

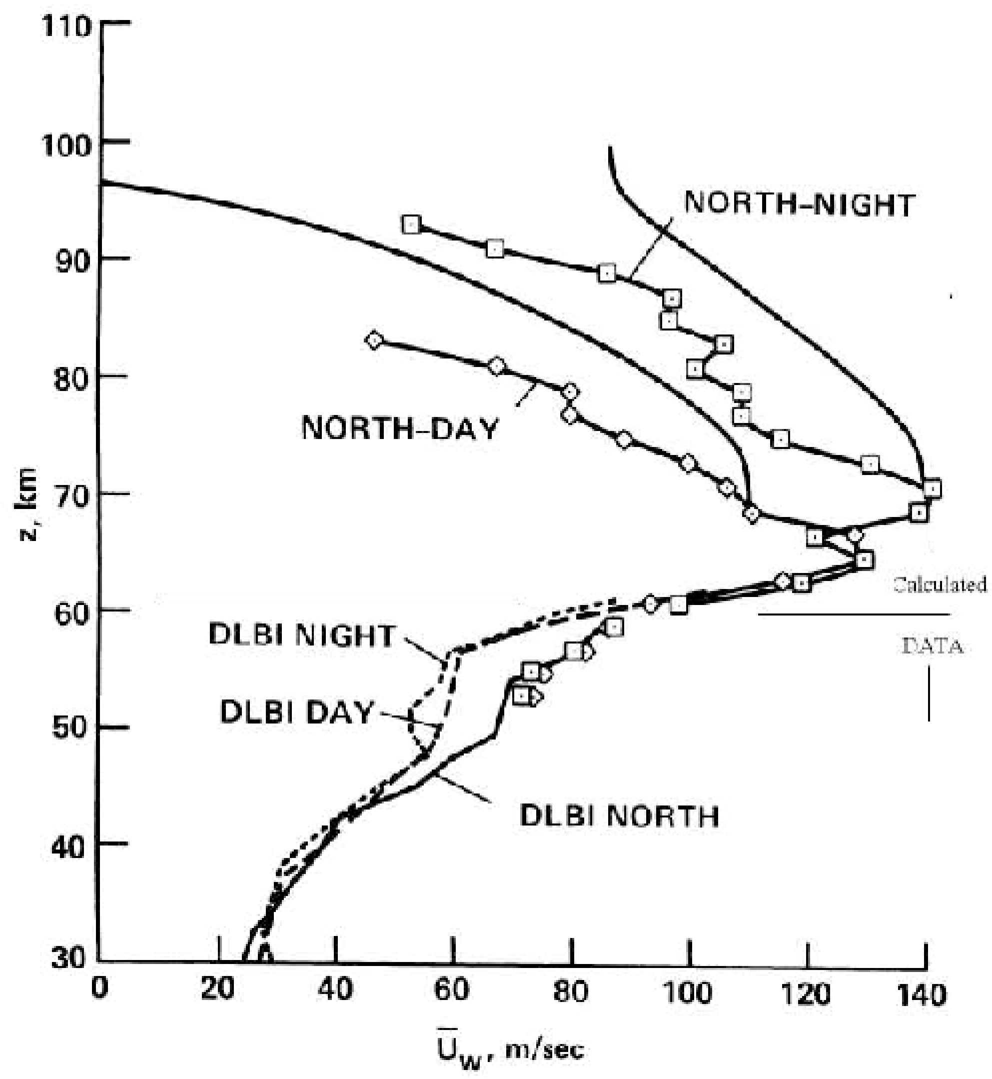
Right: Aerovironment "Pathfinder"

Below: NASA Glenn solar airplane team

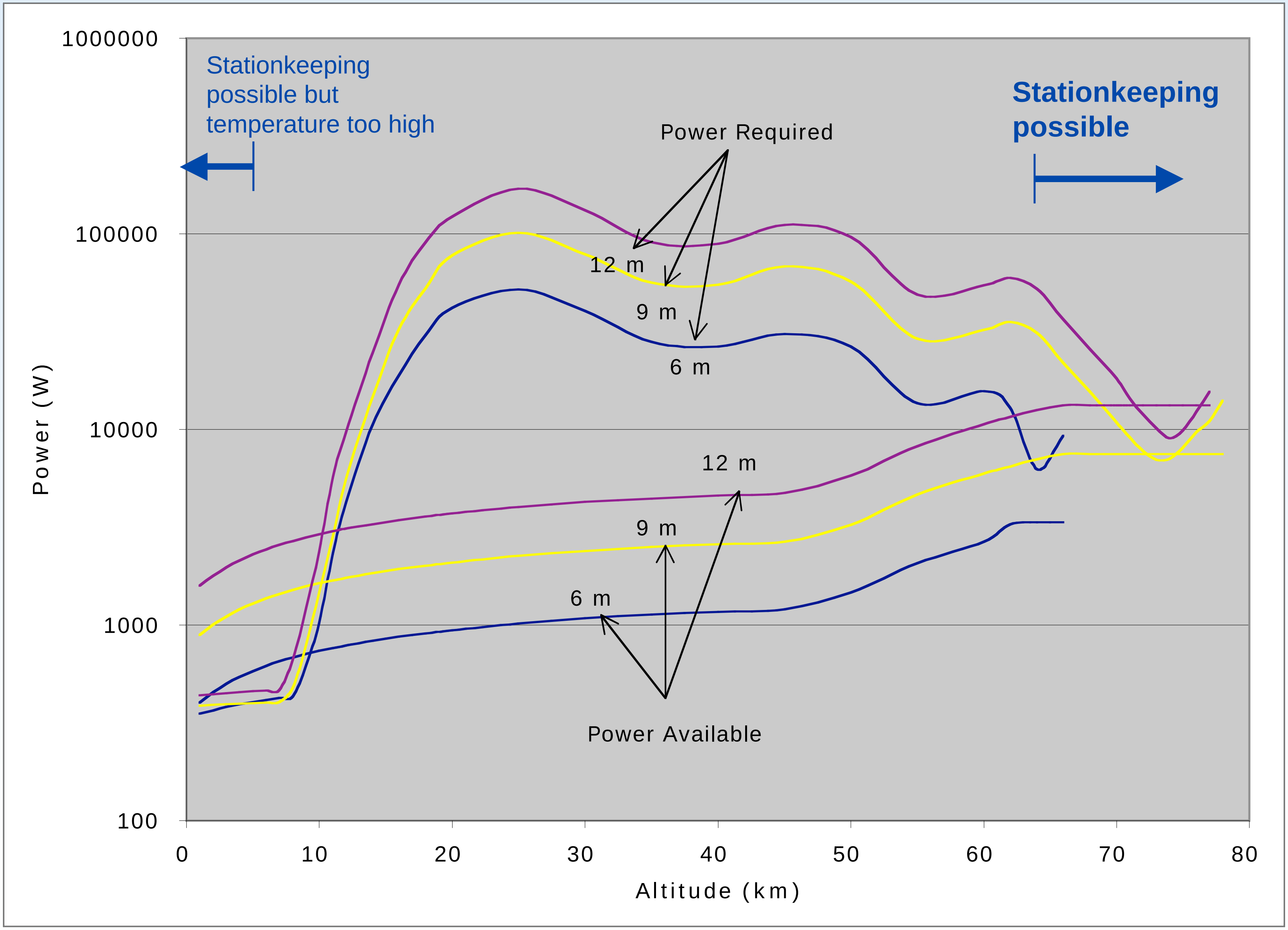


Venus wind

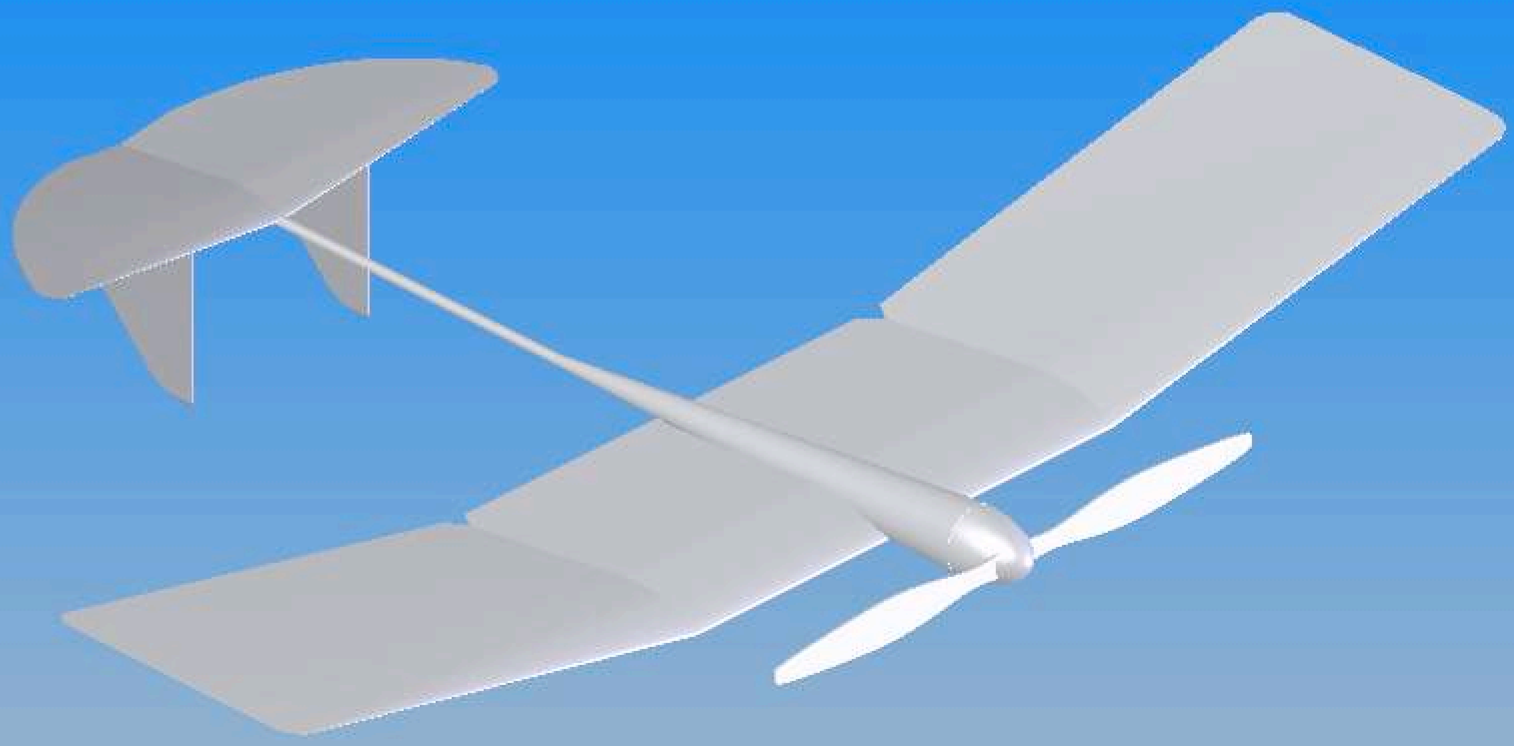
- To stay in constant sunlight, a solar-powered Venus airplane must fly faster than the high-altitude wind



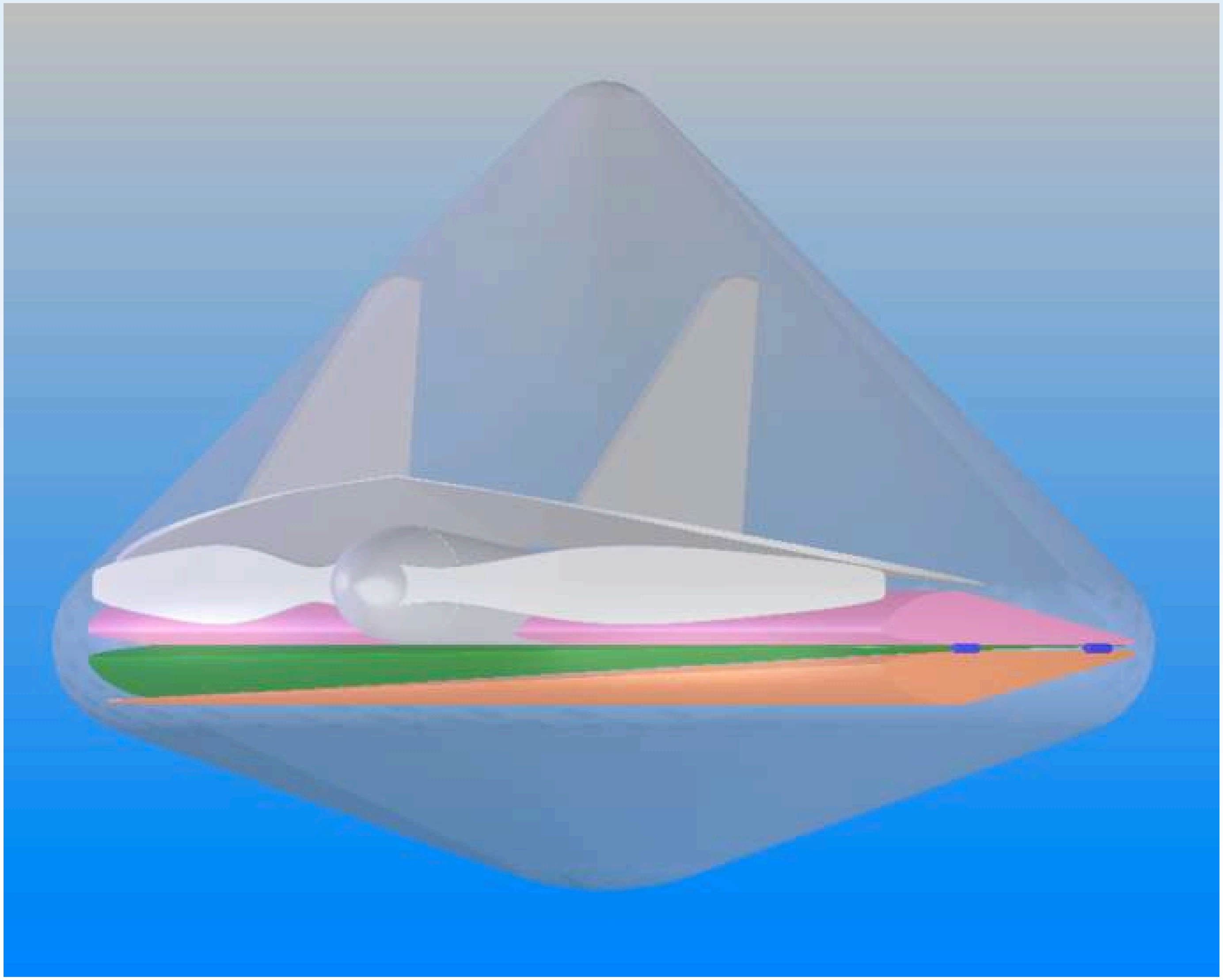
Comparison of winds measured by radio tracking of probes below 60 km with winds estimated from the measured pressures by means of the assumption of cyclostrophic balance. Above 60 km, the winds are inferred entirely from measured pressures.


1000000
100000
10000
1000
100
Power (W)
Stationkeeping
possible but
temperature too high
Stationkeeping
possible
Power Required
12 m
9 m
6 m
12 m
9 m
6 m
Power Available
0
10
20
30
40
50
60
70
80
Altitude (km)

Venus airplane: revised design



Venus airplane folded into aeroshell



Venus element mass summaries

VENUS AIRPLANE MASS SUMMARY

NOTE: Only chage numbers in Blue

System Description	Mass Fraction	Mass (kg)	Source
Airplane	20%	**103**	NA
Heatsheild Structure	**7%**	36.05	Pioneer
Heatsheild TPS	**13%**	66.95	Pioneer
Backshell Structure (Gussets, Separation ftgs, Paint, Vent, etc)	**12%**	61.80	Pioneer
Backshell TPS	**8%**	41.20	Pioneer
Parachute System	**10%**	51.50	Pioneer
Airplane Deployment Mechanism (Separation from Backshell)	**15%**	77.25	Mars Airplane
Misc (COMM, Power, Ballast, etc)	**15%**	77.25	Mars Airplane
Total Entry Mass	100%	515	
Contingency Mass	30%	155	
Total With Contingency		**670**	

NOTE: Mass Fractions Based off Mars Airplane Data Venus Pioneer

RCS System Description	Quanty	Mass (kg)	Source
Hardware	NA	51.9	NA
** Marquardt 100lbf Thruster*	*2*	*8.0*	Historical Data
*** Rockwell 25lbf Thruster*	*6*	*25.0*	Historical Data
Fuel Tank	*1.0*	*5.42*	Historical Data
Oxidizer Tank	*1.0*	*5.409*	Historical Data
Pressurant Tank	*1.0*	*3.655*	Historical Data
Associated Harware (Valves, fittings, line)	*NA*	*4.345*	Historical Data
Propellant/Pressurant	NA	103.9	NA
Fuel	*45.4 liters*	*39.0*	DV = 350m/s
Oxidixer	*45.0 liters*	*64.4*	DV = 350m/s
Pressurant	*NA*	*0.5*	DV = 350m/s
Total RCS Wet Mass		**155.8**	

* Marquardt R-4D-1/10 (Isp 300s, Vac Thrust = 444N, Fuel Biprop - N204/Hydrazine
** Rockwell (Rocketdyne) R-1E-3 Shuttle vernier, Isp = 225s, Vac Thrust 111N, Fuel Mono - Hydrazine

Mass Summary	mass (kg)
Aeroshell Payload Package	670
RCS Dry Mass	51.9
RCS Propellant/Pressurant	103.9
Total Dry Mass	**721**
Total Wet Mass	**825**

VENUS ROVER MASS SUMMARY

NOTE: Only chage numbers in Blue

System Description	Mass Fraction	Mass (kg)	Source %
Rover	50.0%	**330**	NA
Heatsheild Structure	**7.0%**	46.20	Pioneer
Heatsheild TPS	**13.0%**	85.80	Pioneer
Backshell Structure (Gussets, Separation ftgs, Paint, Vent, etc)	**12.0%**	79.20	Pioneer
Backshell TPS	**8.0%**	52.80	Pioneer
Parachute System	**10.0%**	66.00	Pioneer
Lander with Airbags	**0.0%**	0.00	Pioneer
Misc (COMM, Power, Ballast, etc)	**0.0%**	0.00	Pioneer
Total Entry Mass	100.0%	660	
Contingency Mass	7.0%	46	
Total With Contingency		**706**	

Mass Fractions Based off Venus Pioneer Large Probe

RCS System Description	Quanty	Mass (kg)	Source
Hardware	NA	51.9	NA
** Marquardt 100lbf Thruster*	*2*	*8.0*	Historical Data
*** Rockwell 25lbf Thruster*	*6*	*25.0*	Historical Data
Fuel Tank	*1.0*	*5.42*	Historical Data
Oxidizer Tank	*1.0*	*5.409*	Historical Data
Pressurant Tank	*1.0*	*3.655*	Historical Data
Associated Harware (Valves, fittings, line)	*NA*	*4.345*	Historical Data
Propellant/Pressurant	NA	103.9	NA
Fuel	*45.4 liters*	*39.0*	DV = 350m/s
Oxidixer	*45.0 liters*	*64.4*	DV = 350m/s
Pressurant	*NA*	*0.5*	DV = 350m/s
Total RCS Wet Mass		**155.8**	

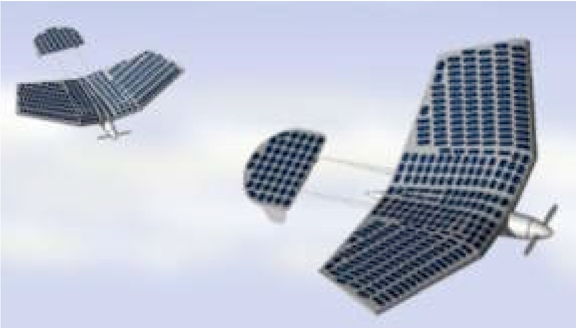
* Marquardt R-4D-1/10 (Isp 300s, Vac Thrust = 444N, Fuel Biprop - N204/Hydrazine
** Rockwell (Rocketdyne) R-1E-3 Shuttle vernier, Isp = 225s, Vac Thrust 111N, Fuel Mono - Hydrazine

Mass Summary	mass (kg)
Aeroshell Payload Package	706
RCS Dry Mass	51.9
RCS Propellant/Pressurant	103.9
Total Dry Mass	**758**
Total Wet Mass	**862**

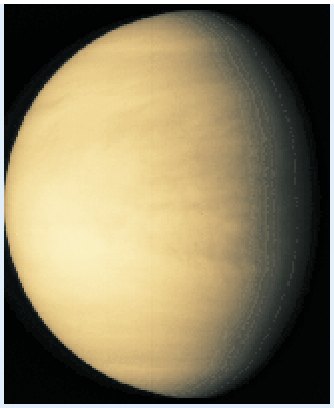
Conclusion:
Venus surface exploration is challenging… but possible

- High-temperature robots on surface
- Computer system in atmosphere
- Communications relay in orbit
- Capability similar to Mars rovers

•Surface and atmosphere exploration project sets the stage for a Venus sample return mission



For More Details:

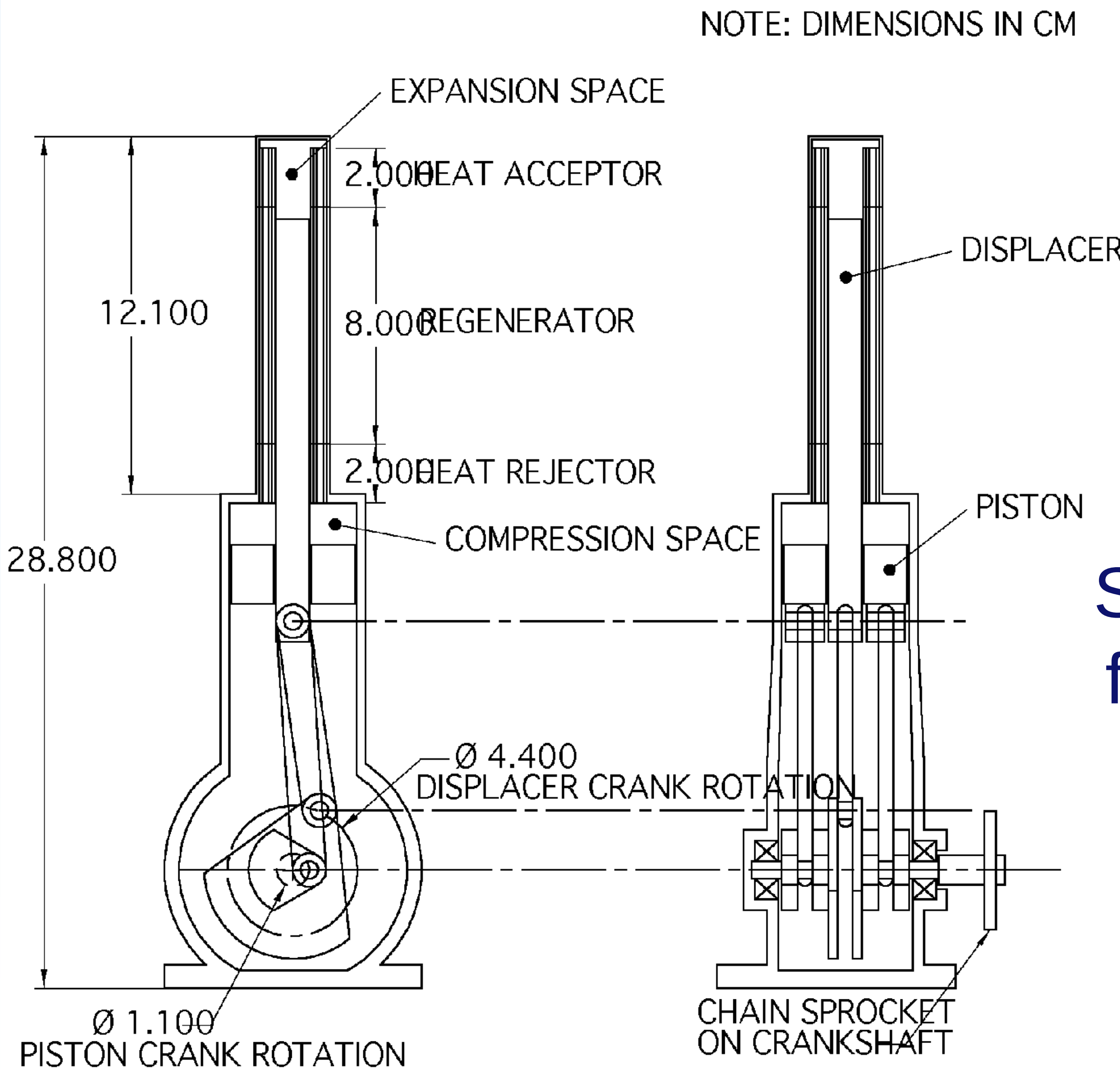


- Web page and movie
  - http://www.grc.nasa.gov/WWW/5000/pep/photo-space/venus-mission-design.htm
- Mission Design:
  - G. Landis, "Robotic Exploration of the Surface and Atmosphere of Venus," *Acta Astronautica, Vol. 59*, 7, 517-580 (October 2006). Paper IAC-04-Q.2.A.08
- Venus Airplane:
  - G. Landis, C. Lamarre, and A. Colozza, "Venus Atmospheric Exploration by Solar Aircraft," *Acta Astronautica, Vol. 56,* No. 8, 750-755 (April 2005). Paper IAC-02-Q.4.2.03
  - G. Landis, C. LaMarre and A. Colozza, "Atmospheric Flight on Venus: A Conceptual Design," *Journal of Spacecraft and Rockets, Vol 40*, No. 5, 672-677 (Sept-Oct. 2003).
- Power and cooling systems:
  - G. Landis and K. Mellott, "Venus Surface Power and Cooling System Design," *Acta Astronautica, Vol 61*, No. 11-12, 995-1001 (Dec. 2007). Paper IAC-04-R.2.06
- High-temperature electronics:
  - P. Neudeck, NASA Glenn *Research & Technology 2005,*
  - NASA/TM-2006-214096
- My home page **http://www.sff.net/people/geoffrey.landis**
- **MIT page: mit.edu/aeroastro/www/people/landis/landis.htm**

High temperature Fuel Cells

Solid Electrolyte CO/O2 fuel cell

- Demonstrated on Earth
- Uses zirconia-based solid electrolyte developed for hydrogen fuel cells
- Reactant is available on Venus
- 500-600C nominal operating temperature, slightly higher than Venus ambient



Stirling Cooler for the Venus Surface