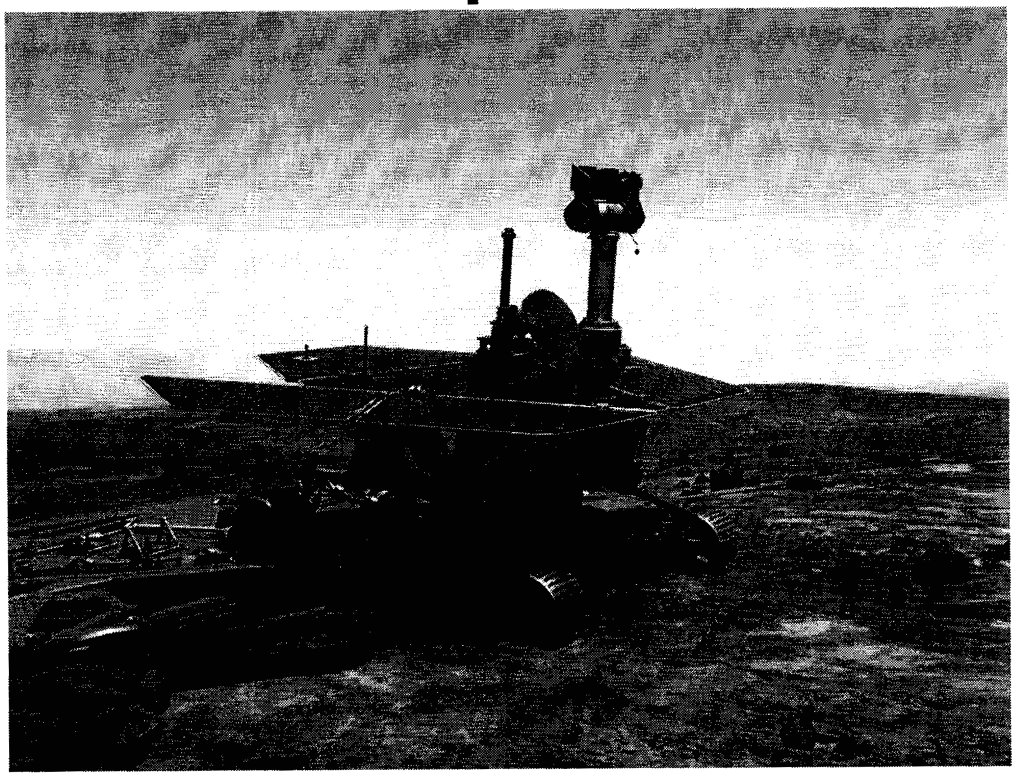
Development of a Thermal Control Architecture for the Mars Exploration Rovers



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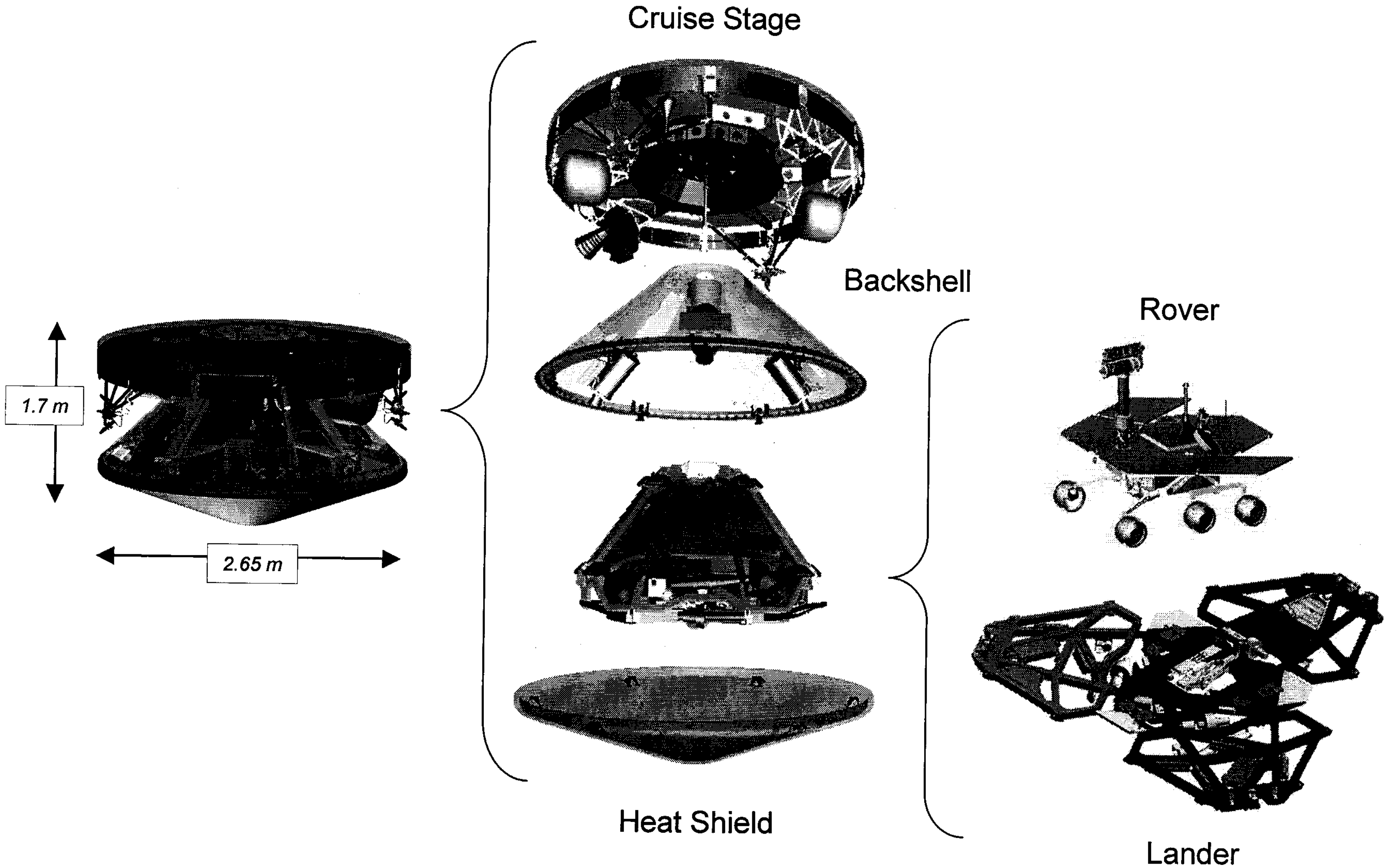
Jet Propulsion Laboratory/California Institute of Technology

STAIF 2003 Conference – Feb. 4, 2003

MER Project Description

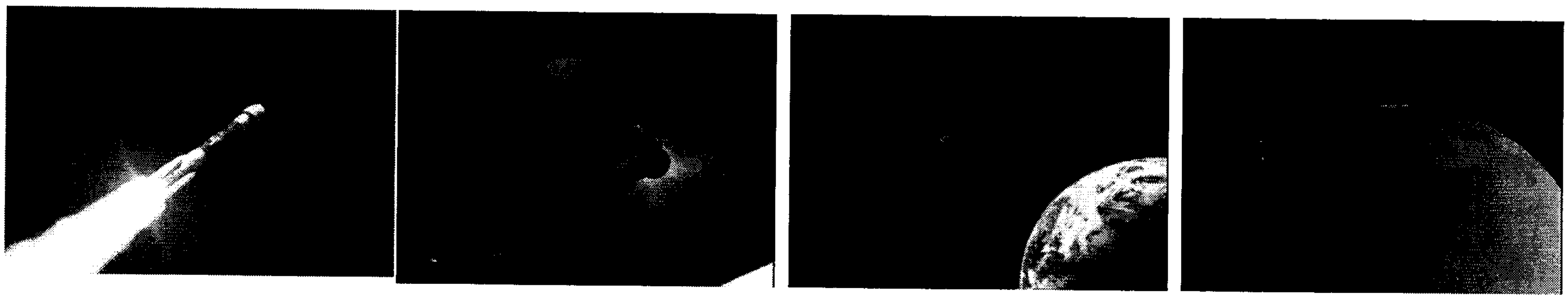
- The Mars Exploration Rover (MER) is a mission to land two identical roving science vehicles on Mars and perform geological science data collection with a surface science operations lifetime of at least 90 sols.
- The missions will launch in the 2003 opportunity (June - July) on separate Delta II class vehicles, land on Mars in Jan 2004, deploy the rovers and conduct surface operations.
  - MER - A is the first launched (May - June 2003), first arriving (early Jan. 2004) flight system.
  - MER - B is the second launched (June - July 2003), second arriving (late Jan. 2004) flight system.
- Each Flight System consists of:
  - A cruise stage and entry, descent and landing system (EDL) with inheritance from the Mars Pathfinder (MPF) development
  - A rover based upon the Athena Rover developments undertaken for the Mars '01 and Mars Sample Return projects (1 km traverse capability)
  - Athena Science Package, 5 science instruments to conduct remote and in-situ observations

MER Spacecraft Configuration

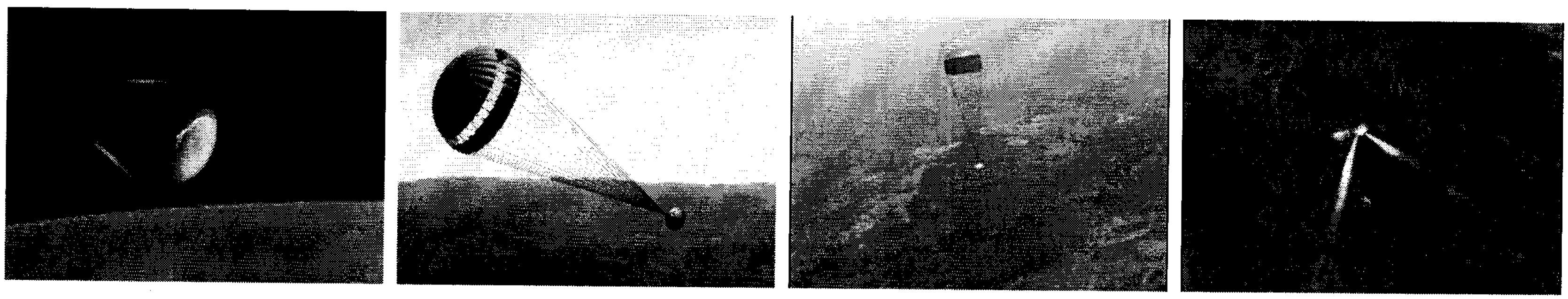


Mission Overview

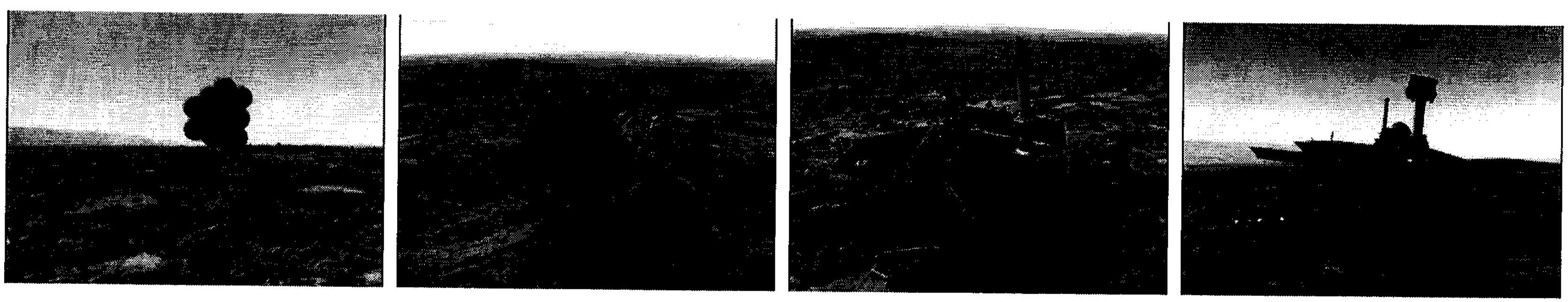
Launch/Cruise



EDL

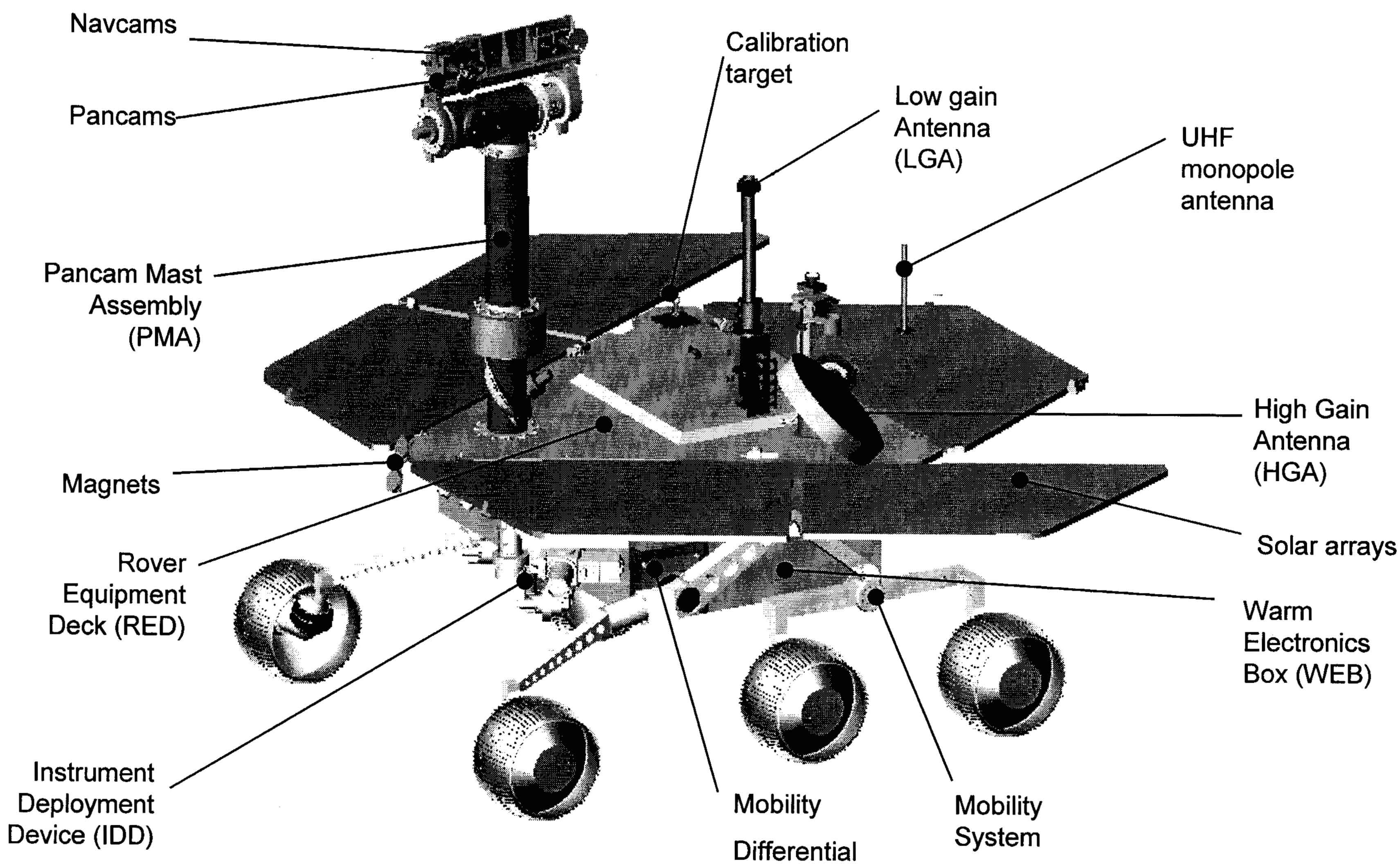


Surface

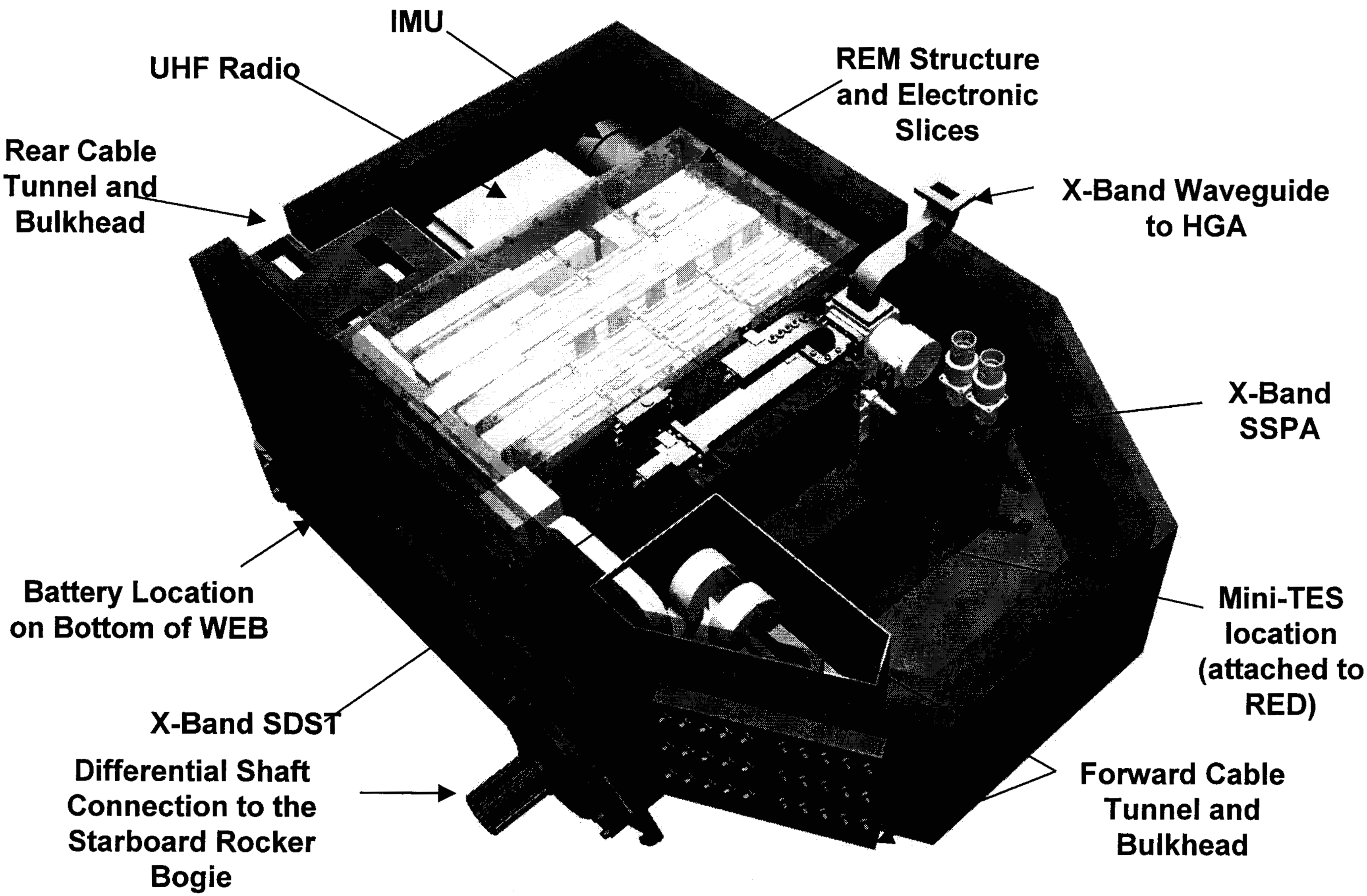


Images From Mission Animation by Dan Maas

Rover Configuration - Deployed



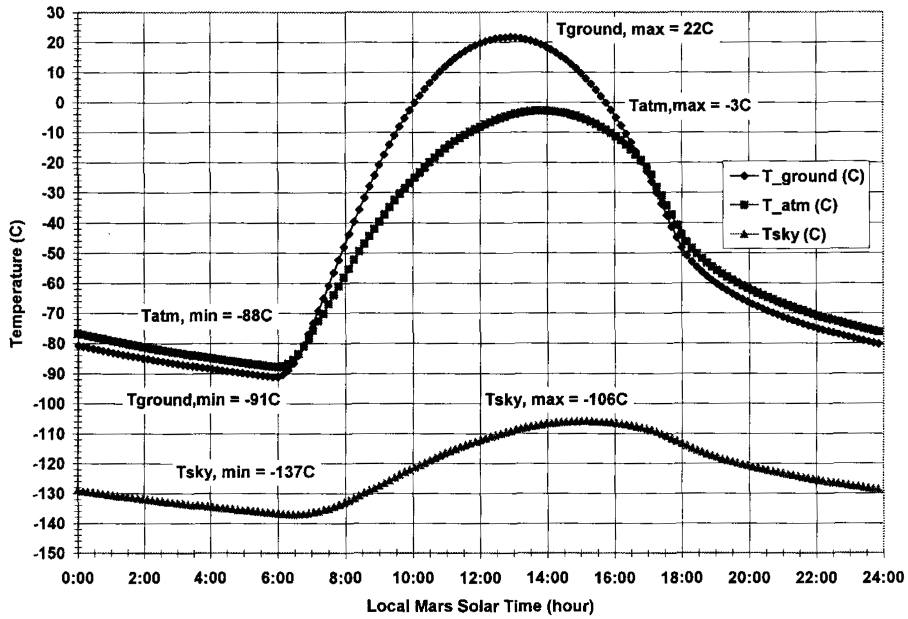
Rover Warm Electronics Box

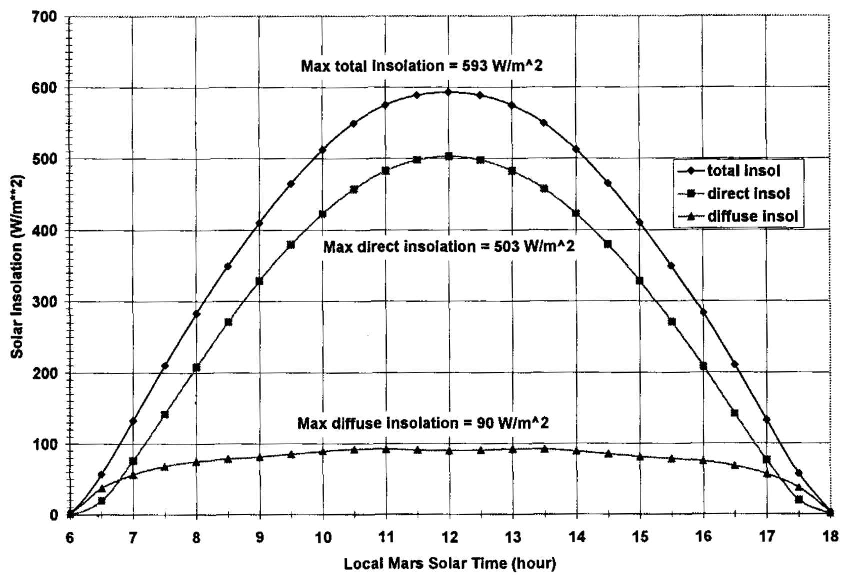


Thermal Design Drivers

- Mars Surface Thermal Environment
- Hardware Temperature Limits
- Electrical Energy Usage Constraints
- High and Low Energy Operational Scenarios

Mars Surface Environment





- Driven by landing site latitude (10°N to 15°S), time of year (L_S = 328 at BOM, L_S = 30 at EOM), ground albedo (0.12 to 0.25) and inertia (rock distribution), dust level (Tau = 0.2) in atm & elevation (-1.3km, MOLA)
- Global Circulation Model predicts ground, atmosphere & sky temps, solar insolation during day
- Wind speeds from Viking data (0 to 20 m/sec)

Hardware Temperature Limits

- Temp Sensitive Hardware Located Inside WEB
  - Li Ion secondary battery (-20°C/+30°C), charging at >0°C
  - Flight System Electronics (-40°C/+50°C)
  - Mini-TES Science instrument (-40°C/+45°C)
- Temperature Robust External Hardware - 9 cameras & 34 actuators (-105°C/+50°C)
  - Deployable Solar Arrays
  - Telecommunications antennas (High Gain, Low Gain, UHF)
  - Robotic arm with science sensors
  - Mobility system
  - Pancam Mast Assembly
  - Cameras (Optics and Electronics)

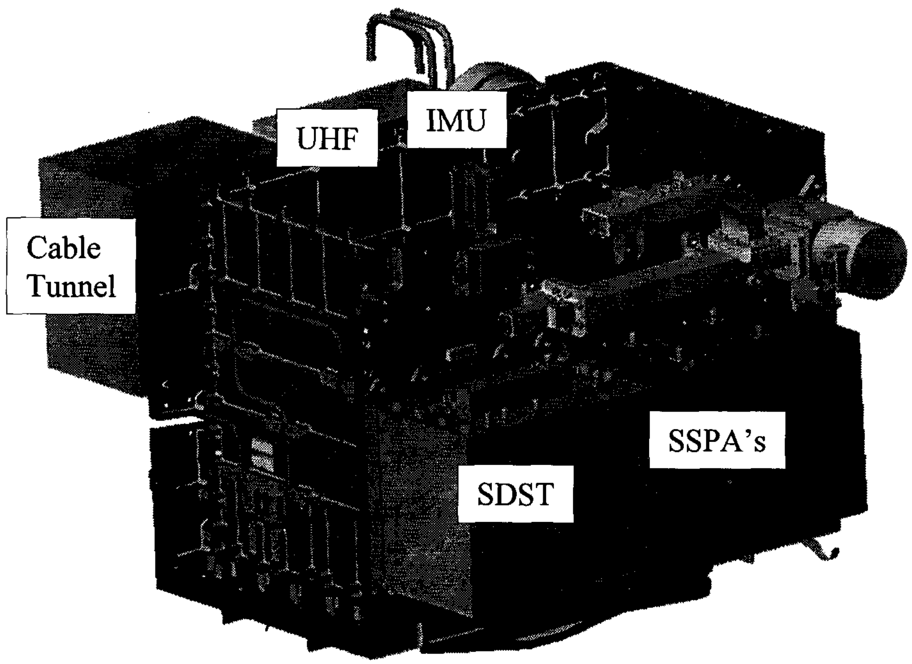
Power System Constraints & Operational Scenarios

- **Power System**
  - 1.3 m^2 deployable solar array with triple-junction GaAs cells
  - Two, 8 A*hr Li Ion rechargeable batteries
  - 600 W*hrs electrical energy production per Sol
  - Bus voltage maintained between 24V and 36V
  - 120 W* hrs available for electrical heater power at night

- **Operational Scenarios**
  - Hot Case – maximum activity, early in mission, 4 hours of DTE comm, 716 W*hrs of dissipation in WEB (100W peak power)
  - Cold Case – late in mission, minimum activity, charge batteries, 470 W*hrs of dissipation in WEB

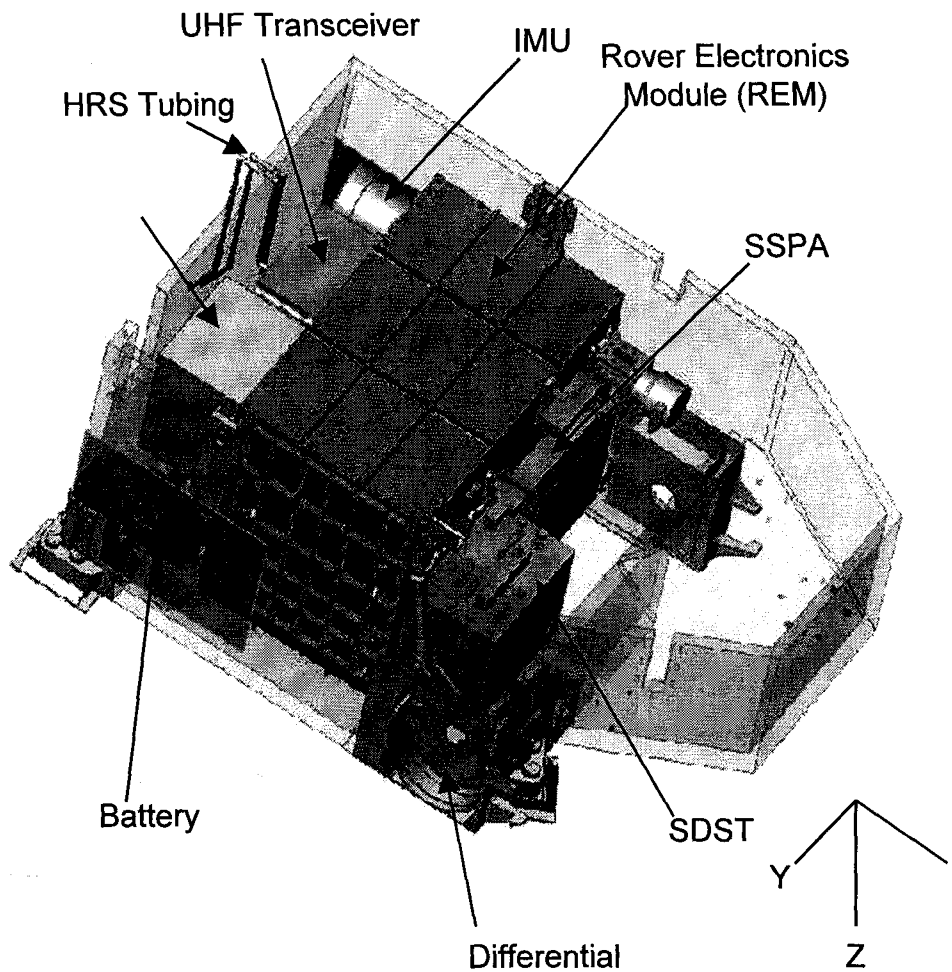
Rover Internal Thermal Design

- **Maximize Thermal Time Constant** (Tau = R * C)
  - Minimize temperature increases driven by internal dissipation profiles and temperature decreases driven by external diurnal environment
  - **Maximize thermal capacitance (C)**
    - Concentrate thermal mass in WEB (36kg) by coupling together
    - Allow power sharing

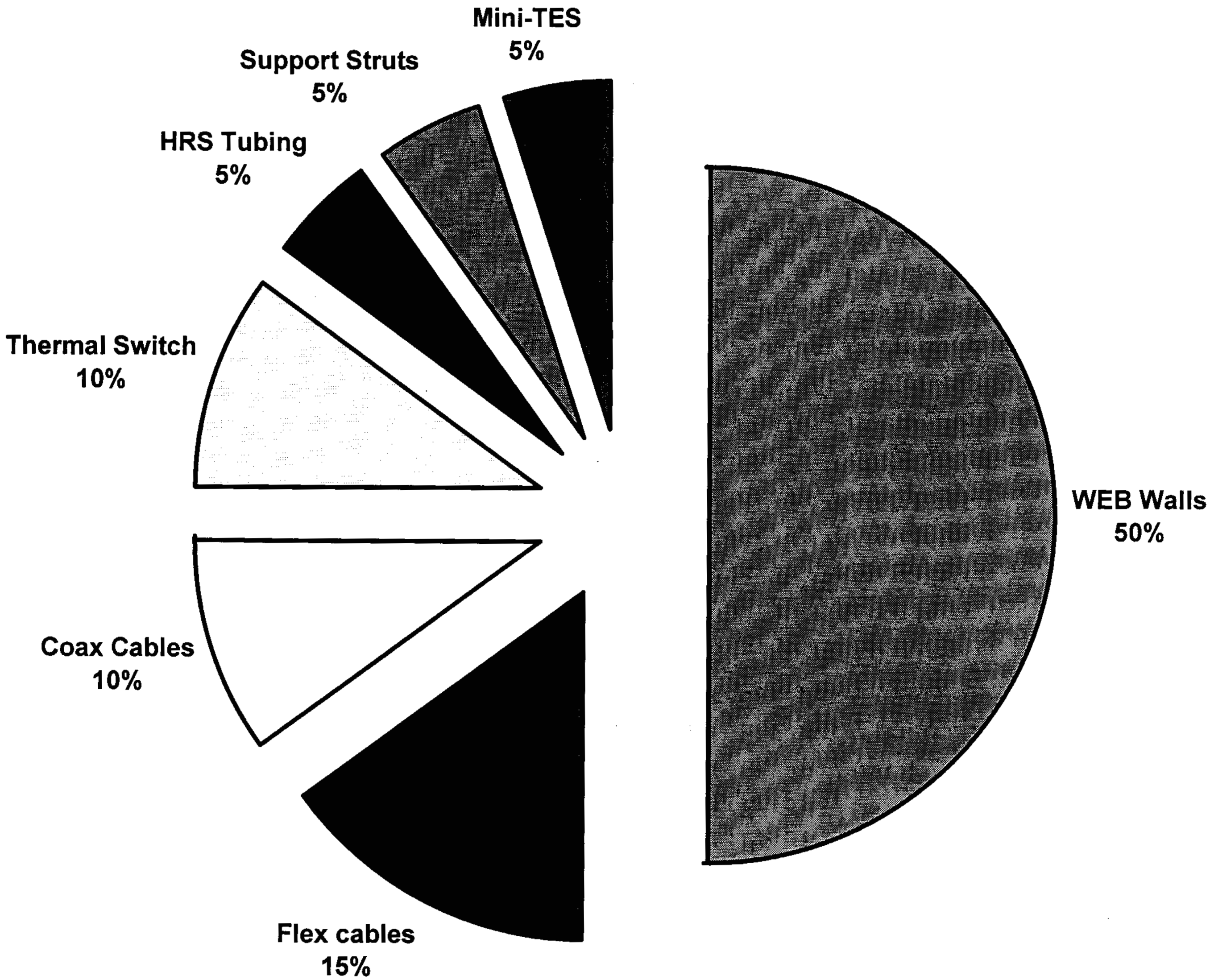


Rover Internal Thermal Design

- **Maximize WEB thermal resistance (R) to environment**
  - Carbon-opacified aerogel insulation (k=0.012 W/m*K)
  - Low emissivity gold internal & external surfaces
  - Flex cables with lower copper cross-section
  - Cable tunnels for flex & coax
  - Battery thermal switches open when battery is cold
  - Stainless steel section of HRS tubing at egress
  - Low conductivity boron-epoxy tubes support H/W



Heat Leaks from WEB

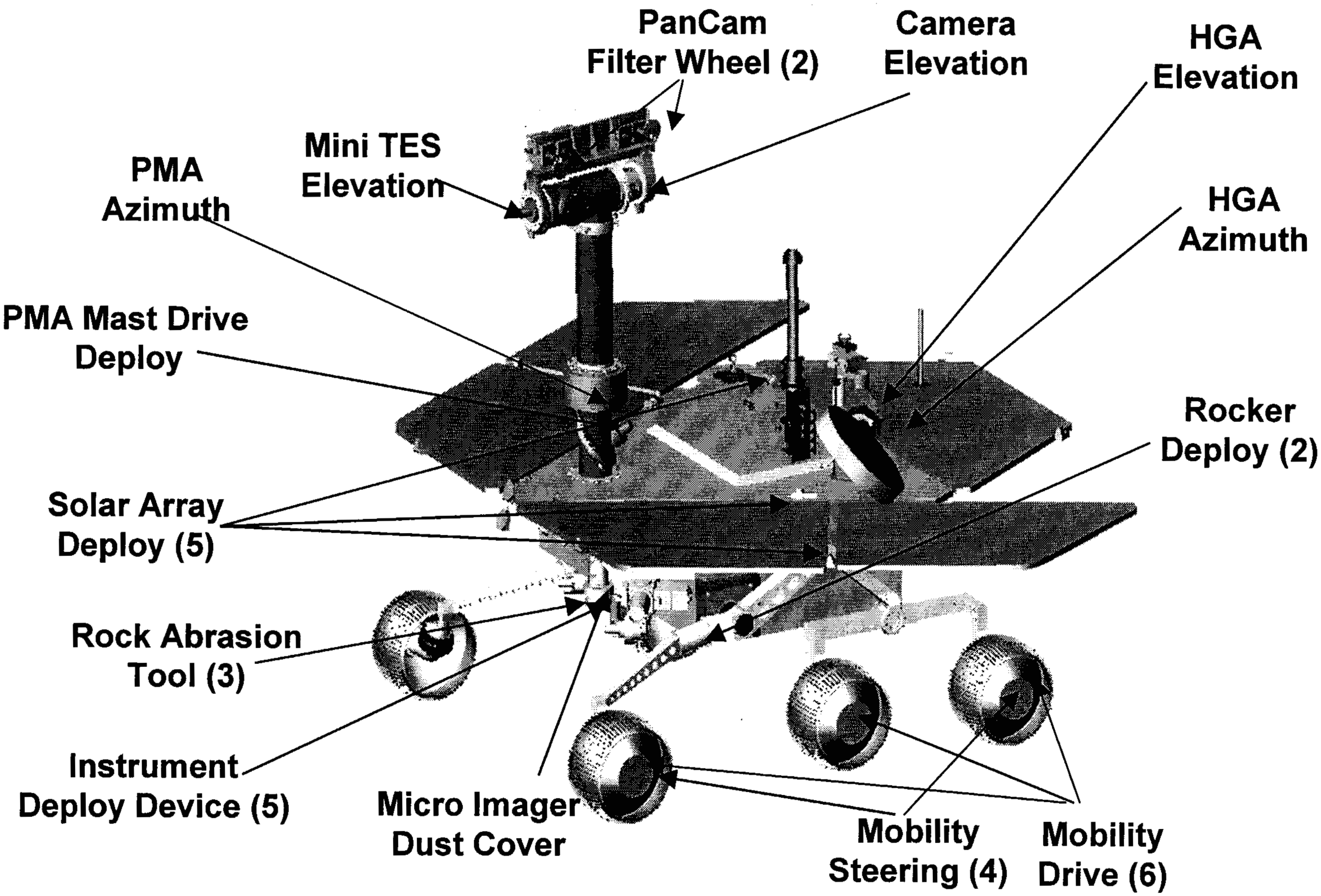


Web Thermal Hardware

- Survival heaters on REM, Battery & Mini-TES
  - Controlled by mech t'stats
  - Operate when flight computer is OFF
- Warmup Heater on Battery
  - Controlled by mech t'stats
  - Warmup to optimal charging temp (0°C)
- Radioisotope Heater Units (RHU's) on REM (2) and Battery (6)
  - Dissipate 1.0 W each
  - Non-electrical heat source; cannot be turned off
- Paraffin-actuated thermal switches between battery & radiator
  - Close when battery temp > 20°C (G=1.0 W/°C)
  - Open when battery temp < 18°C (G=0.017 W/°C)

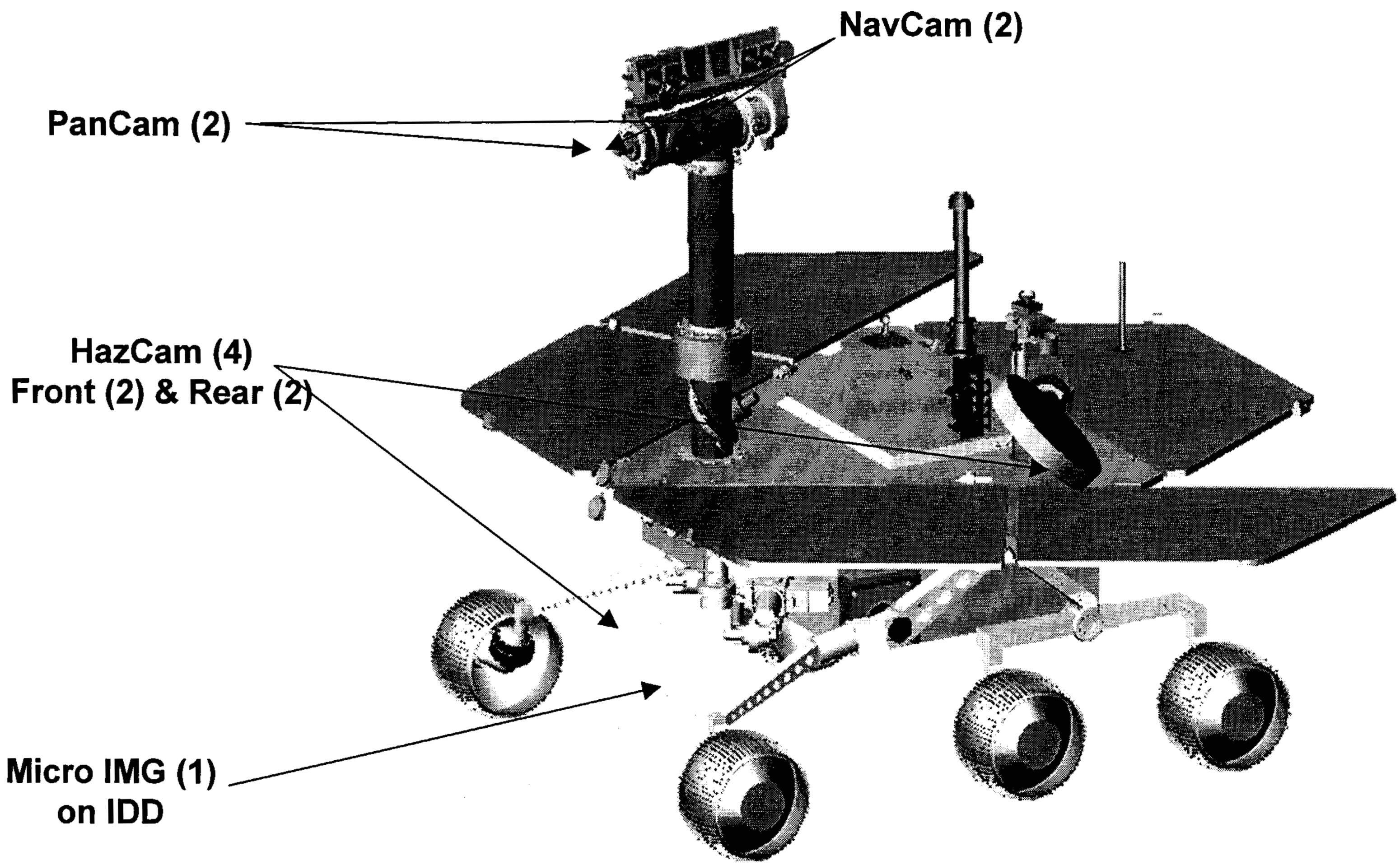
Rover External Thermal Design

- **34 Actuators** on Outside of Rover



Rover External Thermal Design

- 9 Cameras on Outside of Rover



External Thermal Hardware

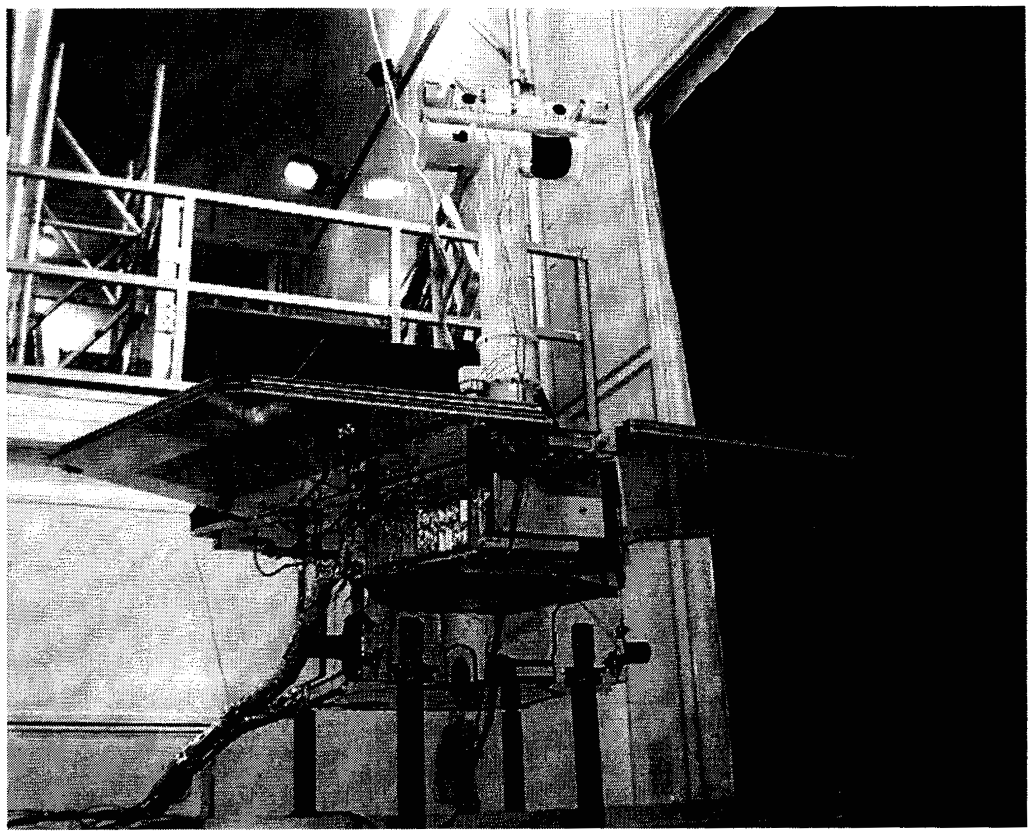
- No survival heaters necessary

- Warmup Heaters (to –55C min op temp)
  - On all actuators (motors, gearboxes, bearings, harmonic drives)
    - Concern is viscosity of Braycote lubricant at cold temps
  - On all camera electronics boards
  - Allow early morning operations

- Low a/e coatings
  - Minimize effect of solar insolation
  - White paint on PMA mast
  - Silvered teflon on motors and gearboxes
  - Silvered teflon on camera electronics housings

Engineering Model Thermal Testing

- **Design validation in Mars environment done by analysis**
  - Direct empirical validation is very difficult on Earth
- **Thermal testing used to obtain data needed to correlate analytical models**



Thermal Test of
Engineering Model Hardware
May 2002

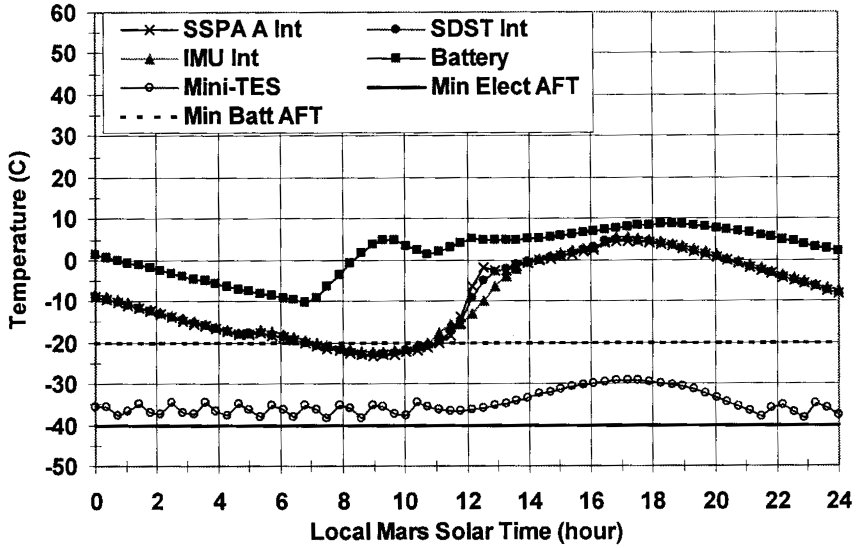
- Derive thermal resistance values from steady state tests
- Derive thermal capacitance values from diurnal transient tests

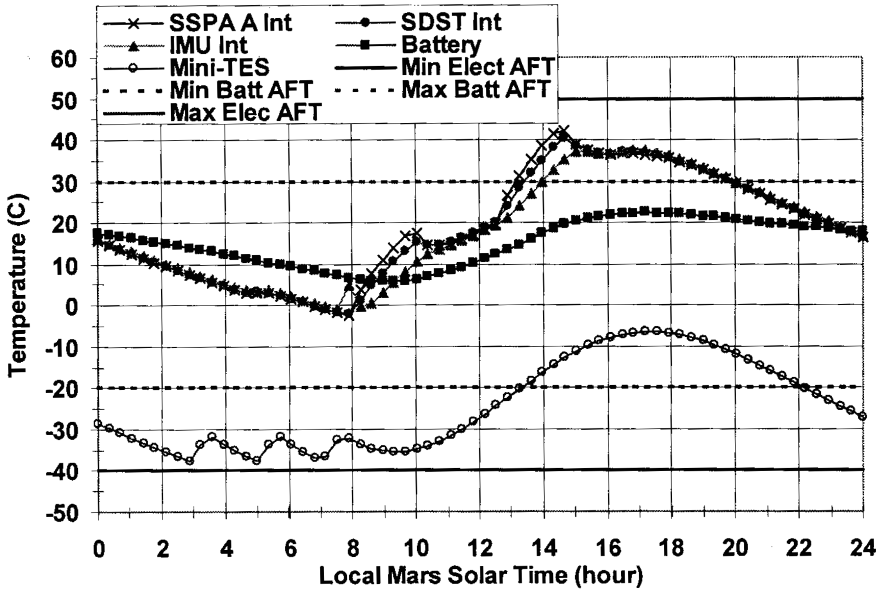
Thermal Testing

- **Comparison of Mars Environment and Chamber Environment**

Environment	Mars	Chamber
Atmosphere	8 torr CO_2	8 torr GN_2
Gravitational Acceleration	3/8 G	1 G
Solar Insolation	Up to 600 W/m^2	none
Boundary Temperatures	T_{sky} = -140°C to -105°C T_{atm} = -95°C to 0°C T_{ground} = -100°C to 20°C	T_{sky} = -95°C to 0°C T_{atm} = -95°C to 0°C T_{ground} = -100°C to 20°C
Wind Speed	0 to 20 m/sec	None, free convection only

Correlated Thermal Model Predictions





<u>Cold Case Results</u>

Low Energy Scenario (470 W*hrs)

Mini-TES survival heater on at night

Battery warmup heater on in AM

Nighttime energy usage 65 W*hrs

(well under max allowable of 120 W*hrs)

<u>Hot Case Results</u>

High Energy Scenario (716 W*hrs)

SSPA on for 4 hours

(exceeds requirement by 1 hour)

Max SSPA temp = 44C

(under max allowable of 50C)

Max Battery temp = 22C

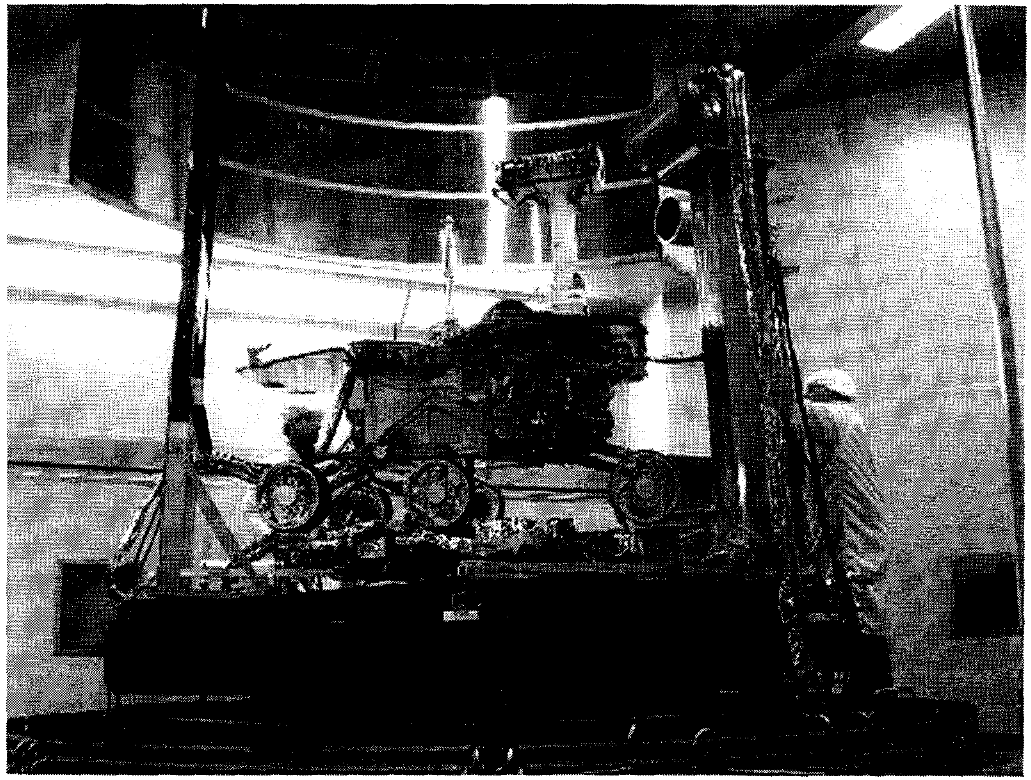
(under max allowable of 30C)

Flight Model Thermal Testing

- **Preliminary design validation in Mars environment done by comparison to previous EM test data**
  - **Followed up by model correlation**
- **Correlated models to be used in operations to predict Mars surface performance**

Thermal Test of
Flight Model Hardware
Dec. 2002

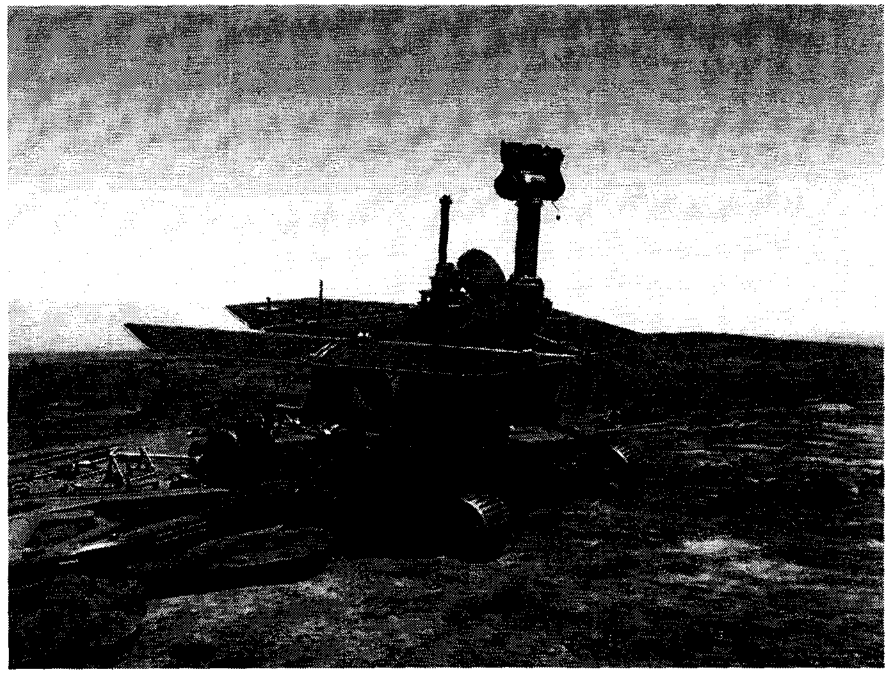
- Compare steady state and transient results to previous EM test
- Generate warmup heater characterization data



Conclusion & Status

System Level Thermal Design

- Exceeds performance requirements
- Requires low night heater energy
- Allows 4 hours of communications
- Highly successful design

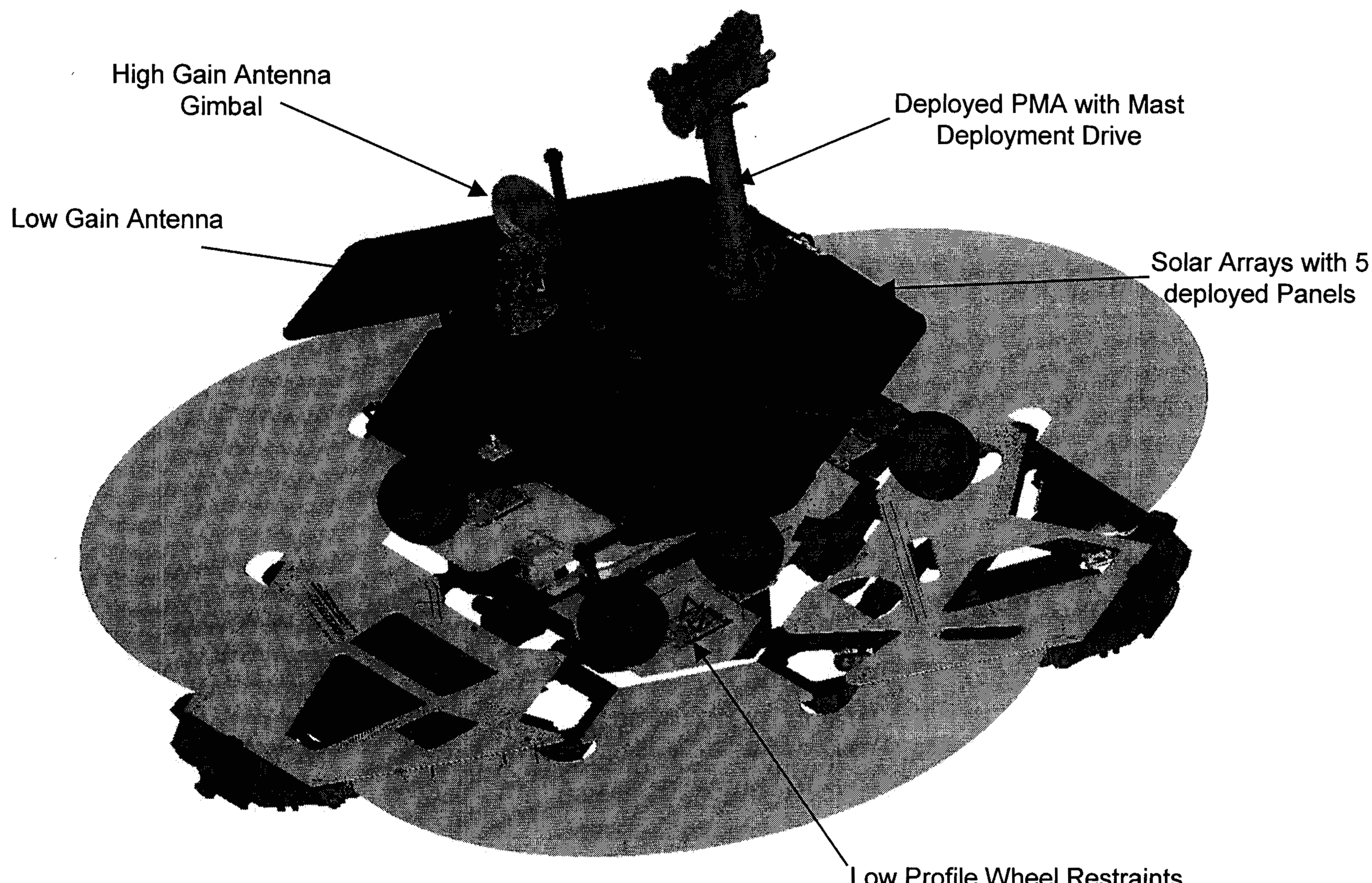


Current project status

- Thermal test of 2nd rover in Feb. 2003
- First launch May 30, 2003
- First landing Jan 4, 2004

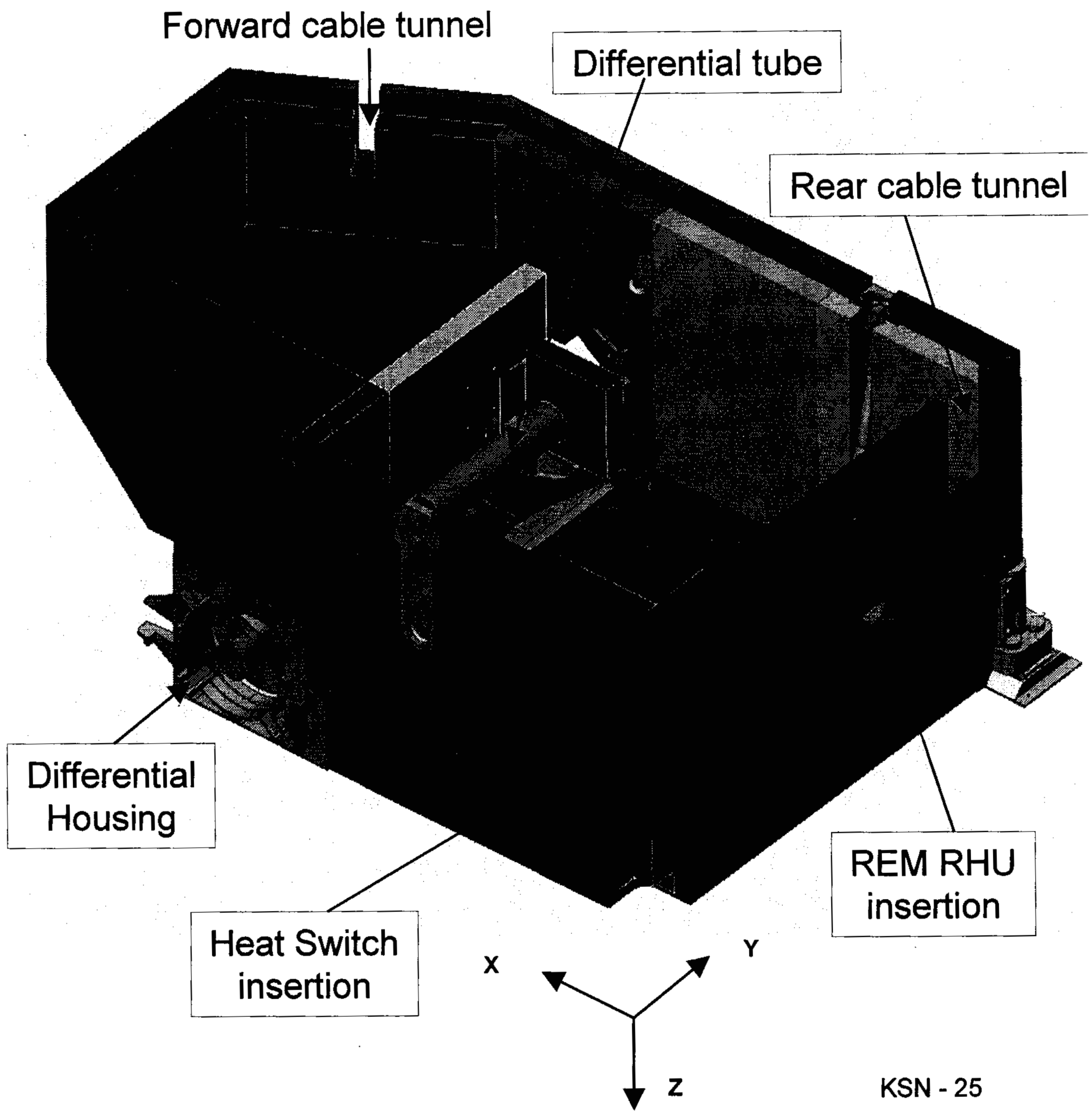
Backup Slides

I. Rover Configuration - Deployed on Lander

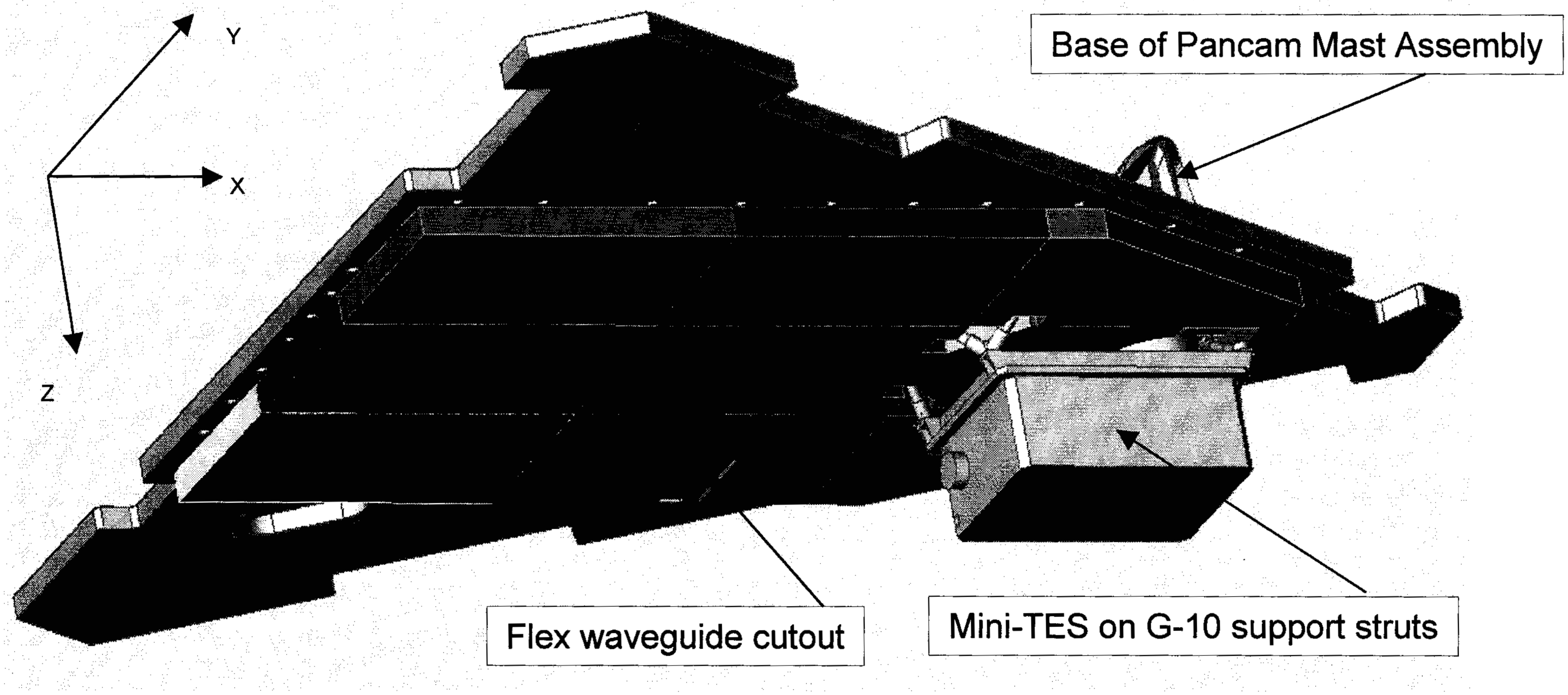


III. Thermal Design Approach - Exoskeleton WEB w/ Aerogel

- 1mm thick M55J Carbon composite facesheets
- over 3.1 lb/ft³ 5056 Al H/C core, 13mm thick side walls, 8 mm thick on bottom wall
- 25 mm of carbon-opacified solid aerogel insulation on all walls except +Z (20mm)
- significant cutouts (6% of area) in aerogel for struts, fittings, cable tunnels, RHU insertion, heat switches
- 0.012" thick Astroquartz composite faceskin closeout on local 0.020" thick "Z" spars

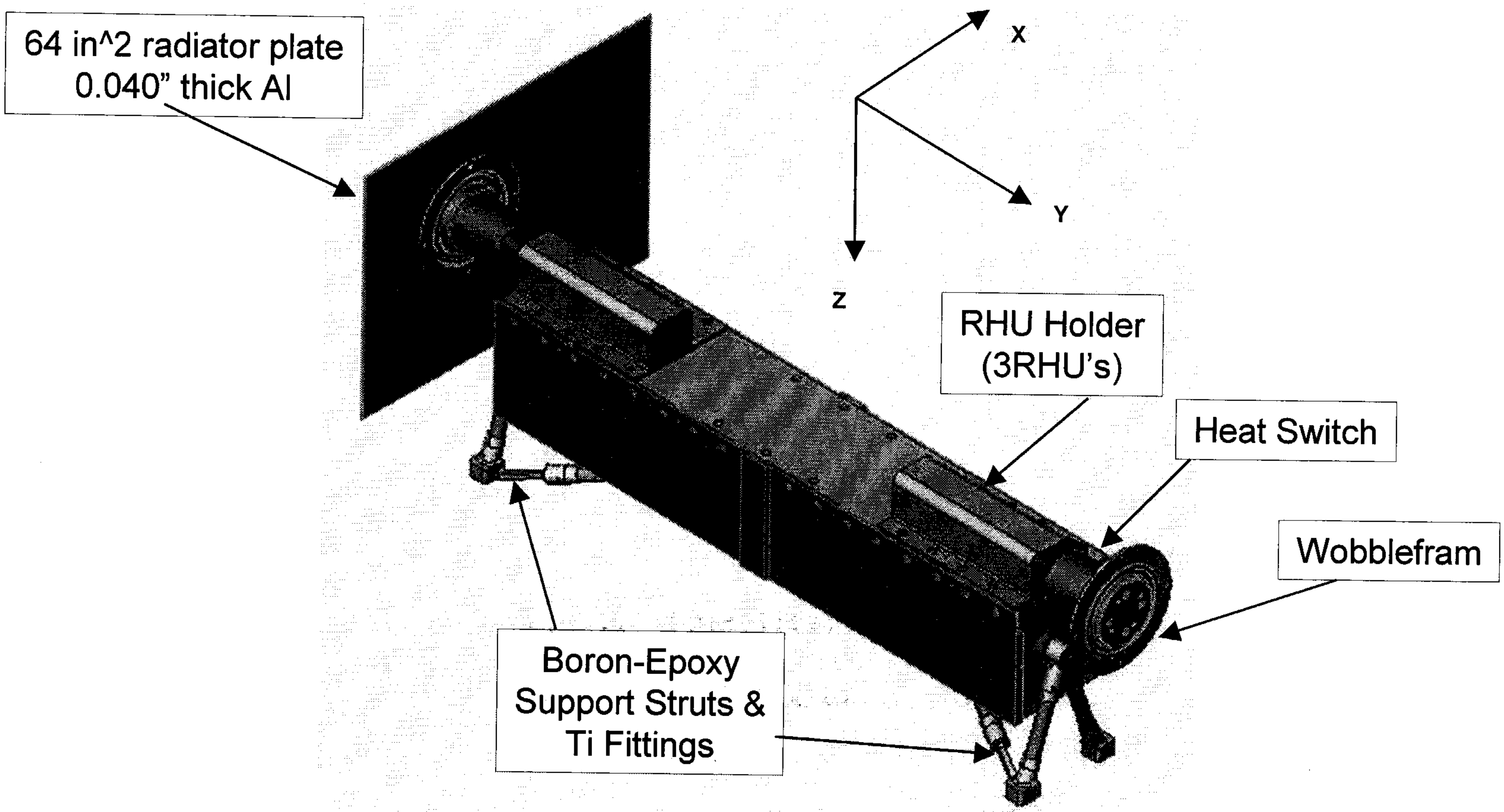


III. Thermal Design Approach - RED w/ Aerogel & REM w/ Struts



- 25mm thick carbon-opacified aerogel
- Cutouts for MTES telescope & LGA flex waveguide

III. Thermal Design Approach - Battery Mounted on Struts



TGMM Description
PMA Cameras Configurations