Driving Rovers on Mars:

Challenges and Opportunities associated with Robotic Planetary Explorers

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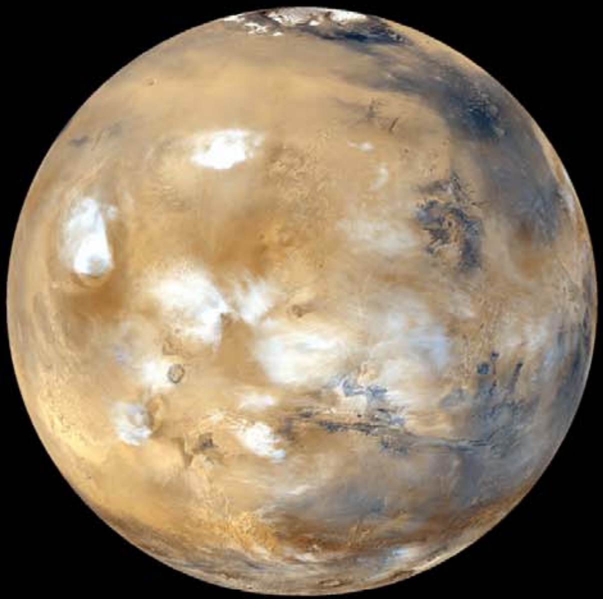
MER Instrument Positioning System Test and Ops Lead

MER Rover Driver

Michigan Technological University

April 15, 2004

Mars: Our Sister Planet



Mars Science Strategy: Follow the Water!

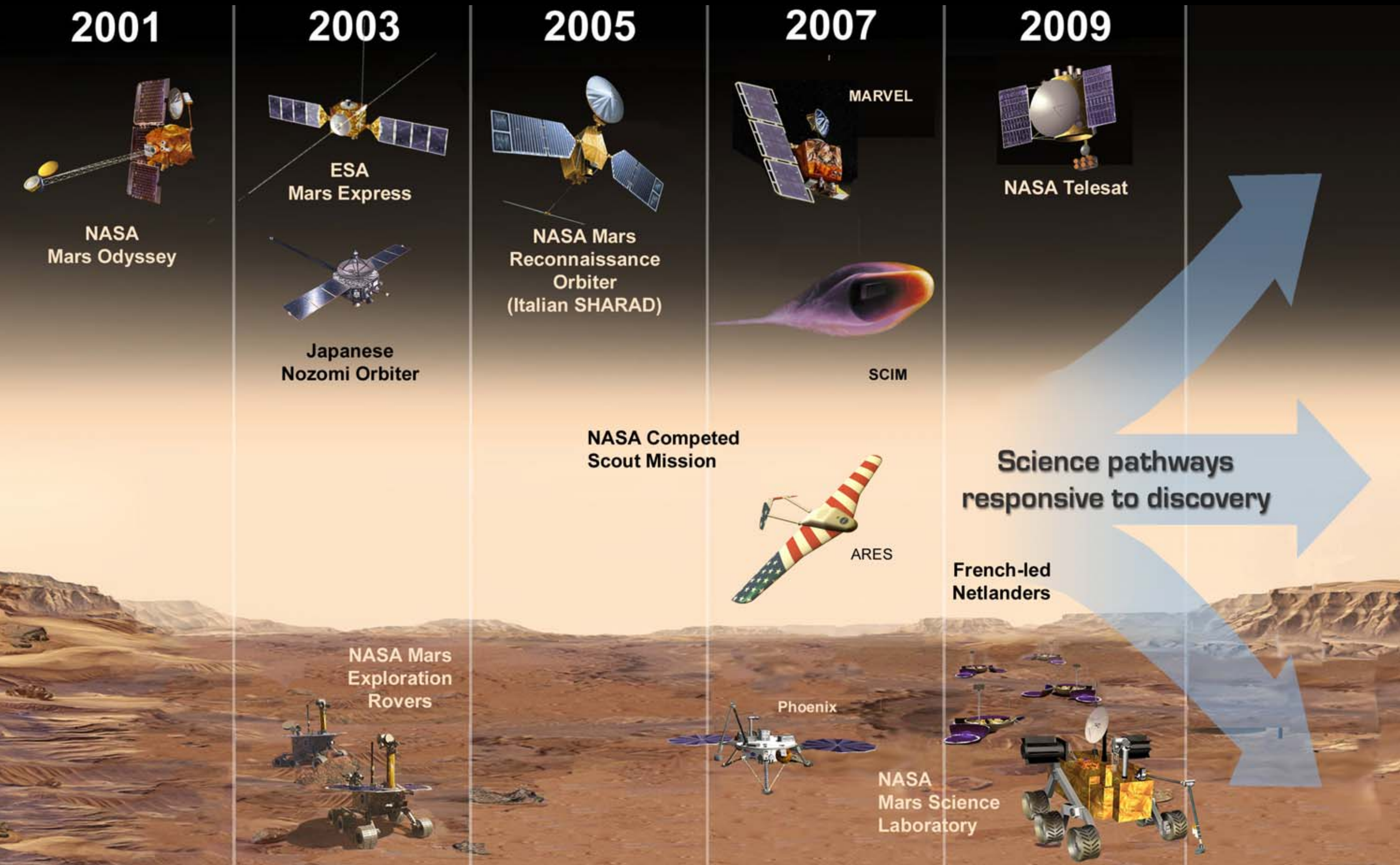
Common Thread

W A T E R

When? Where? Form? Amount?

Determine if Life Ever Arose on Mars	LIFE
Characterize the Climate	CLIMATE
Characterize the Geology	GEOLOGY
Prepare for Human Exploration	HUMAN

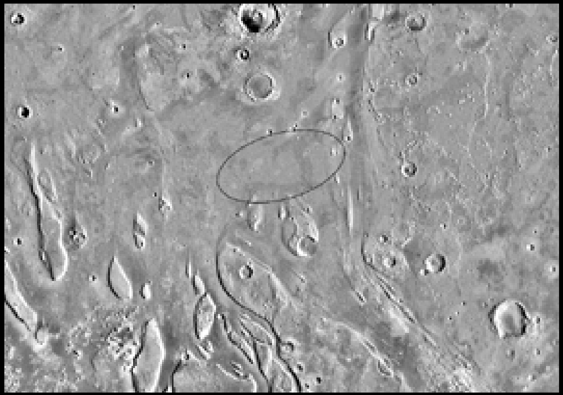
Mars Missions: 2001-2009



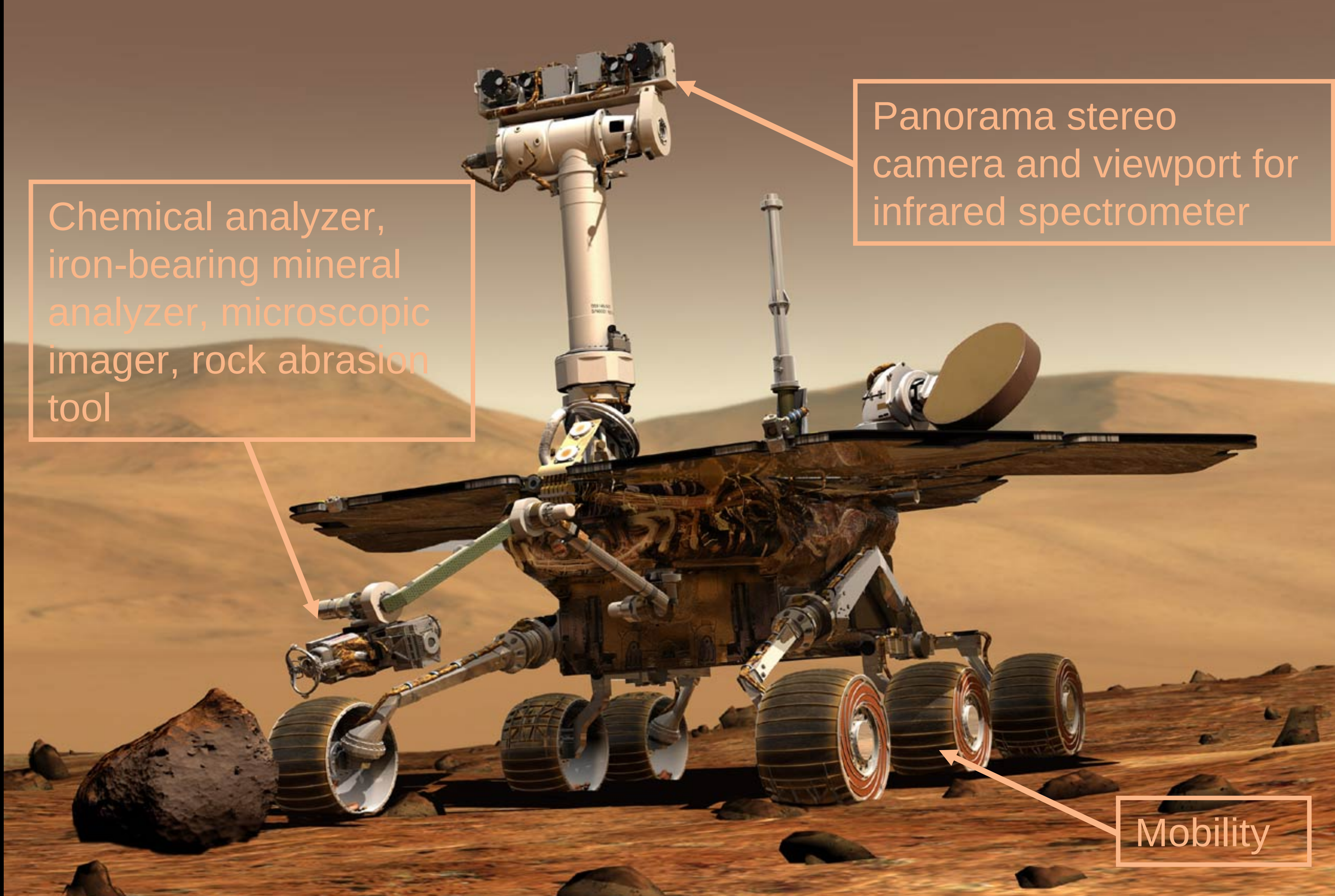
Mars Exploration Rover (MER) Science Objectives

To determine the water, climate, and geologic history of two sites on Mars where evidence has been preserved for past and persistent liquid water activity that may have supported biotic or pre-biotic processes.

The history of Mars and its water is recorded in the rocks

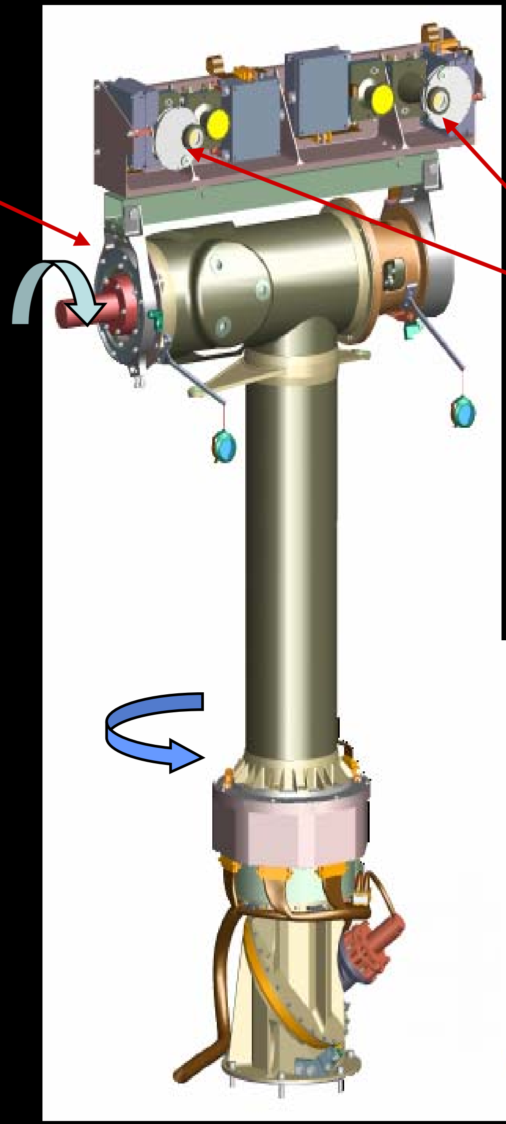


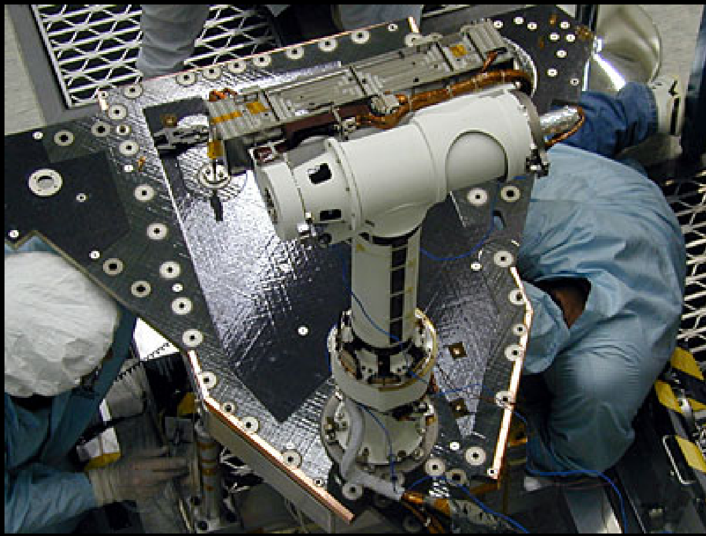
Robotic Field Geologists!



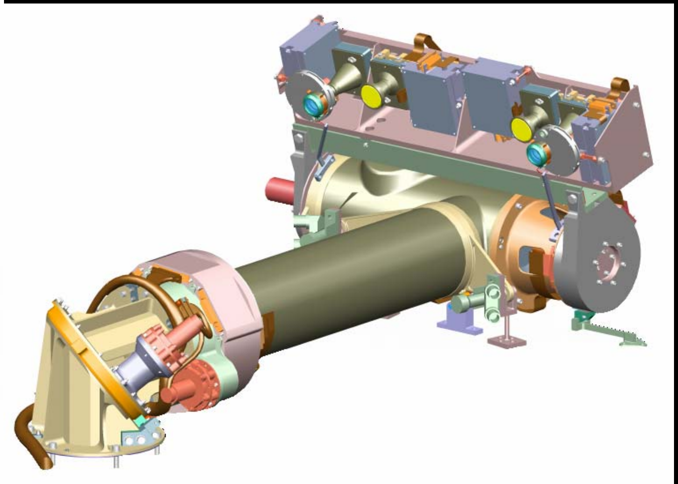
Mast-Mounted Science

Mini-TES
infrared
spectrometer
viewing port



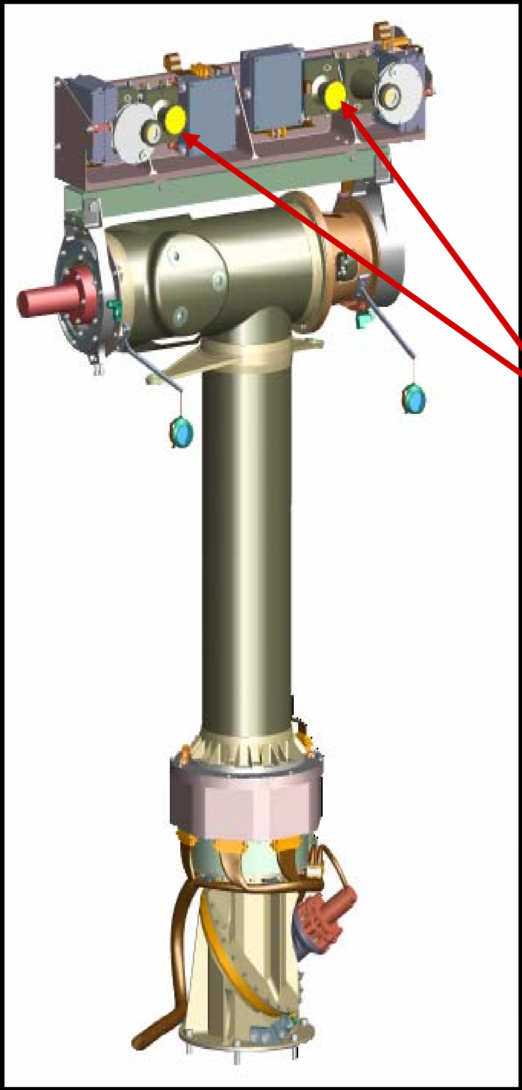


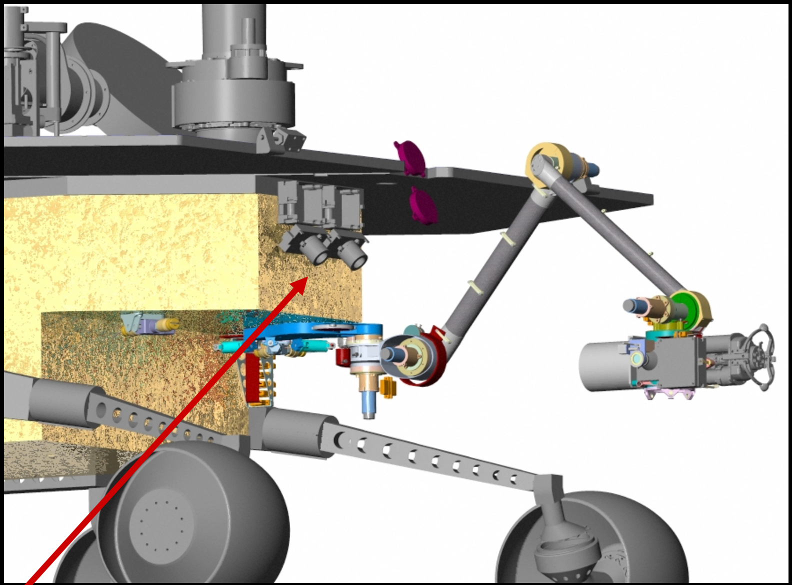
Pancam color stereo
panorama cameras
17º FOV



Mini-TES

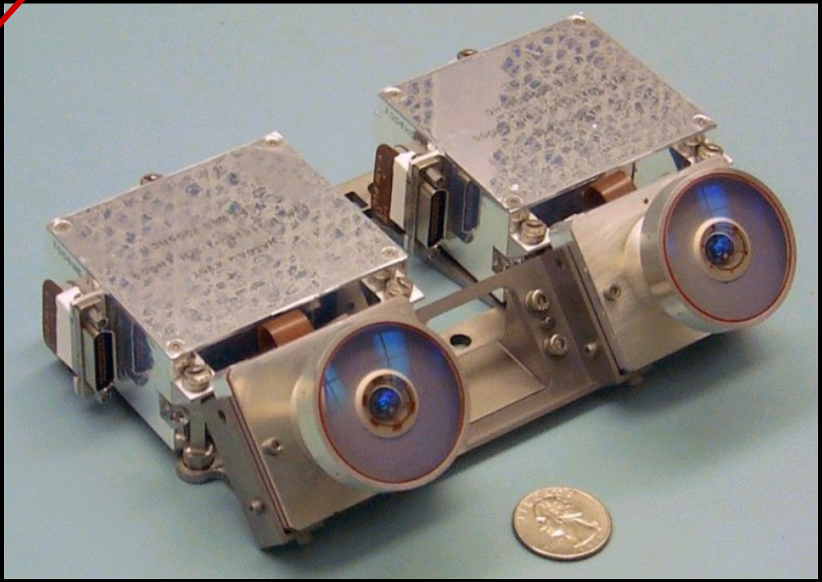
Engineering Cameras



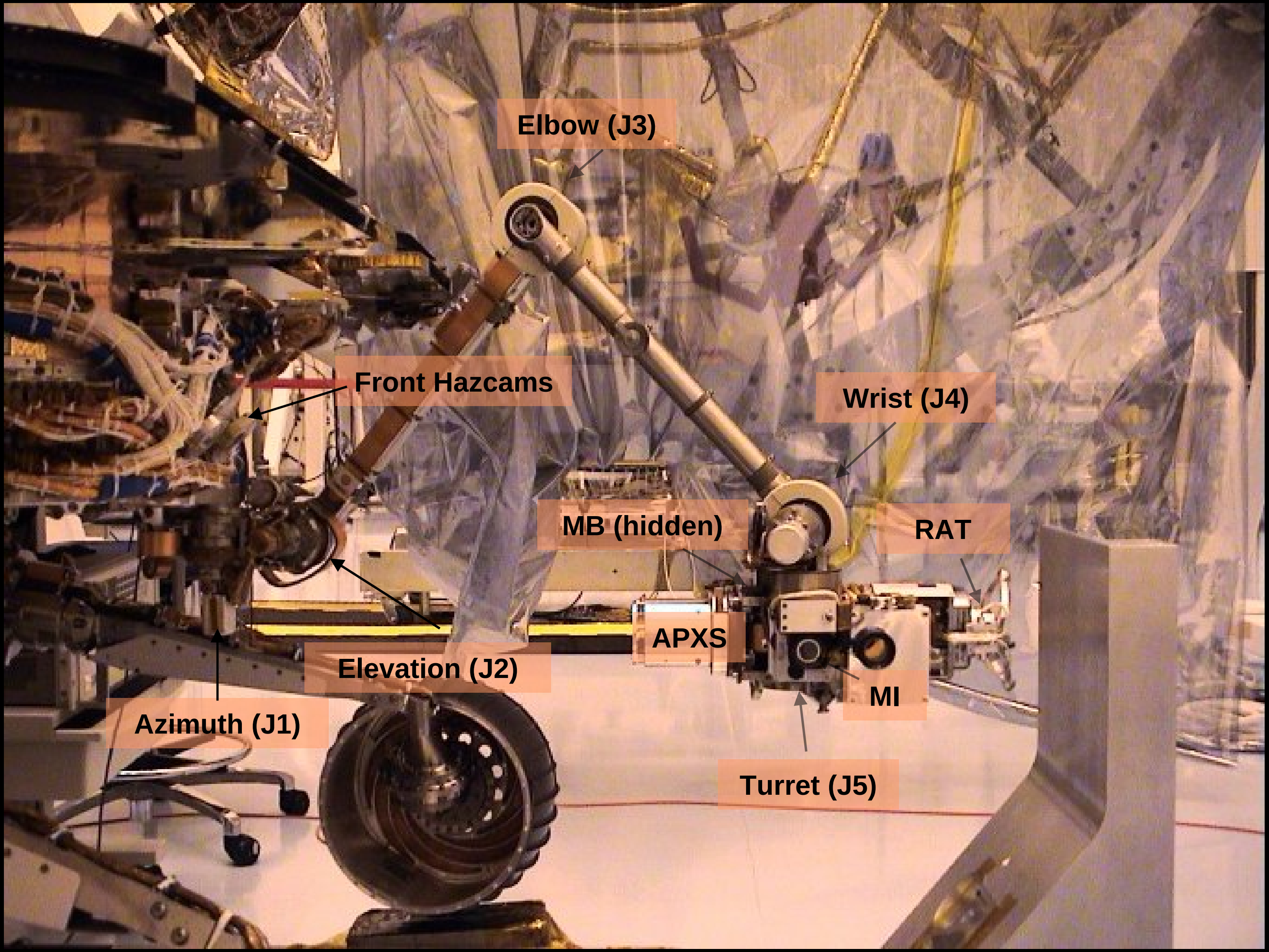


Navcam
stereo cameras
45º FOV

Front and Rear Hazcam
stereo cameras
120º FOV

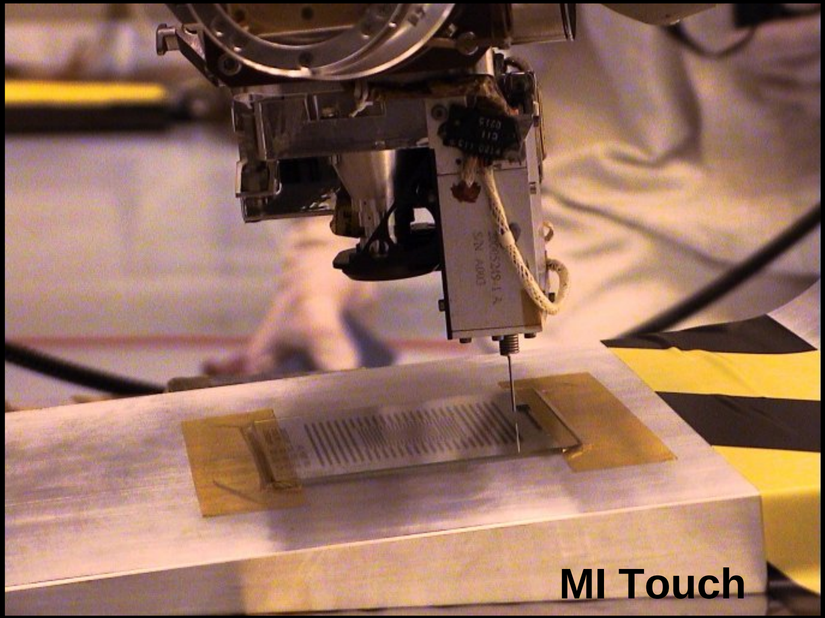


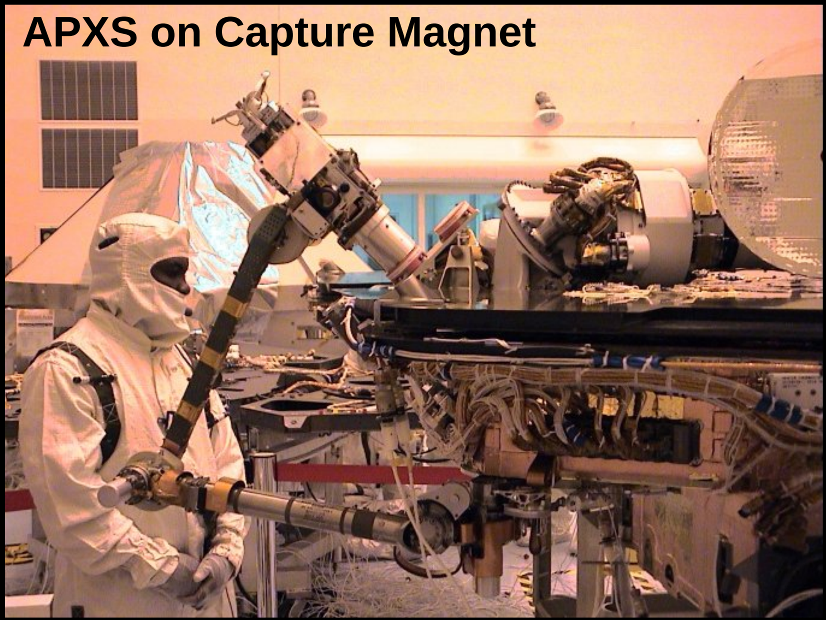
Instrument Positioning System



Instrument Deployment Device (IDD)

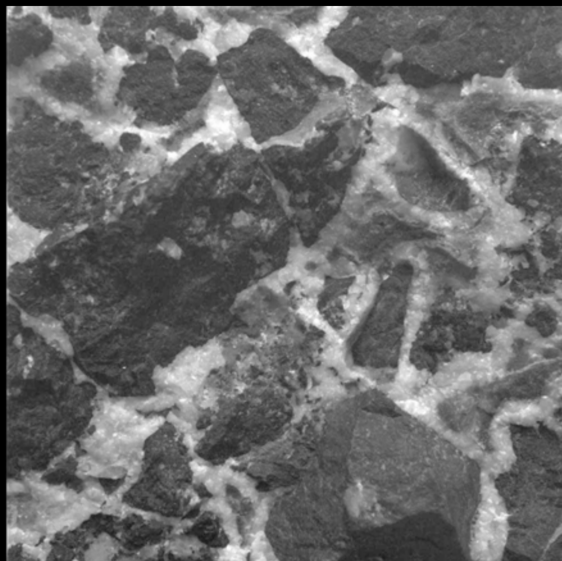
- The IDD is a 5 degree-of-freedom robotic manipulator that controls the 3D position (X, Y, Z) and 2D orientation (azimuth and elevation) of the in-situ instruments mounted to the IDD turret with respect to rock and soil targets



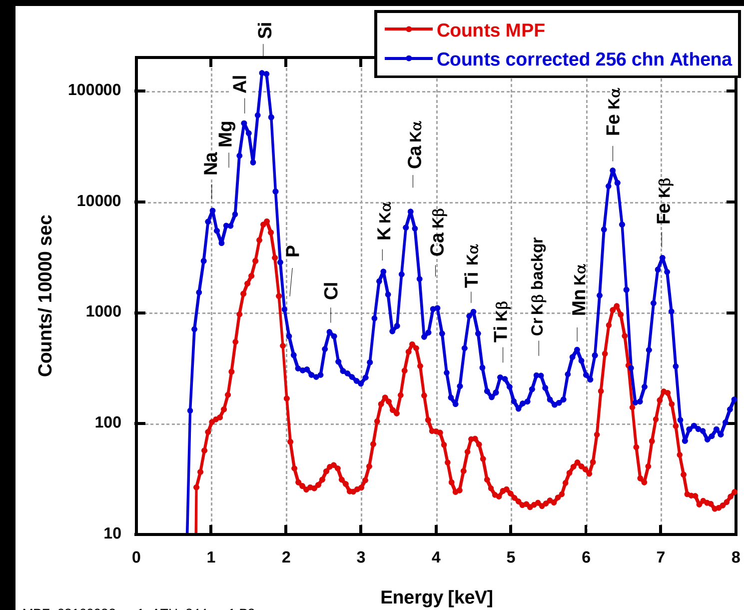


In-Situ Science Payload

Microscopic Imager Image

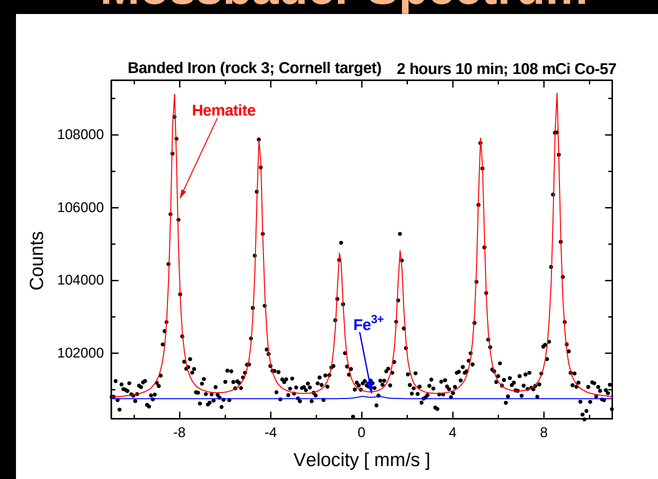


APXS Spectrum

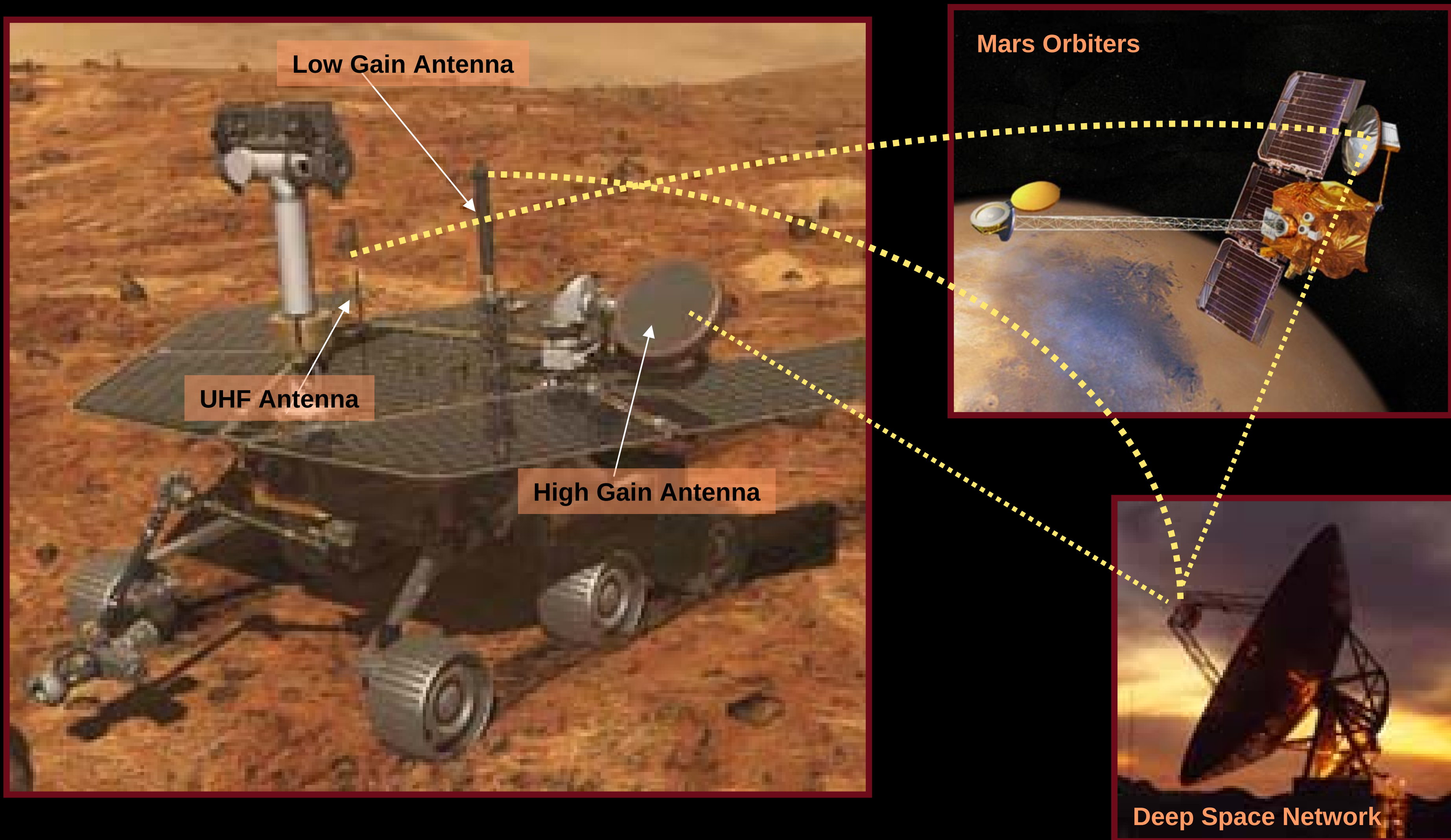


RAT Abraded Surface

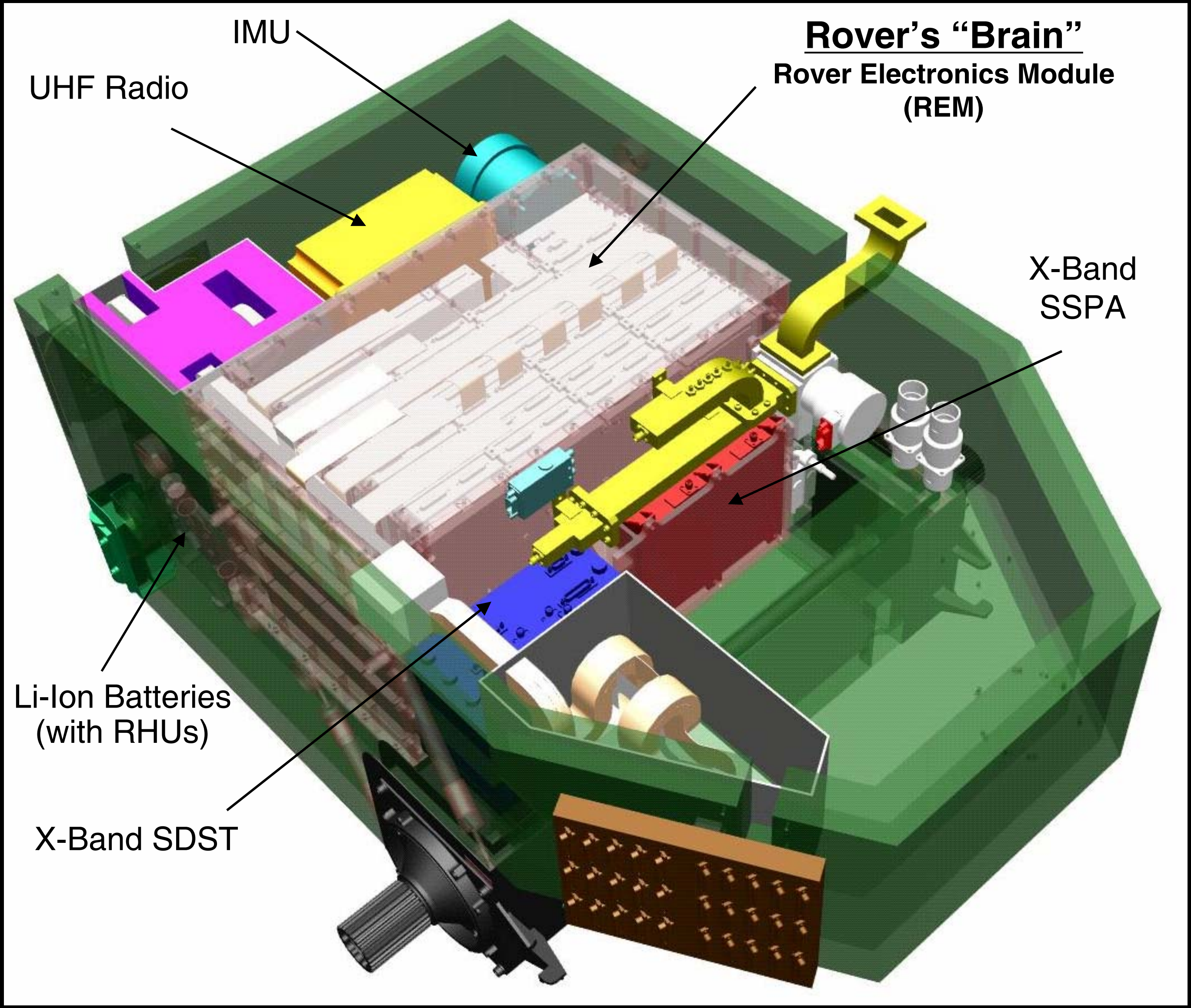
Mössbauer Spectrum



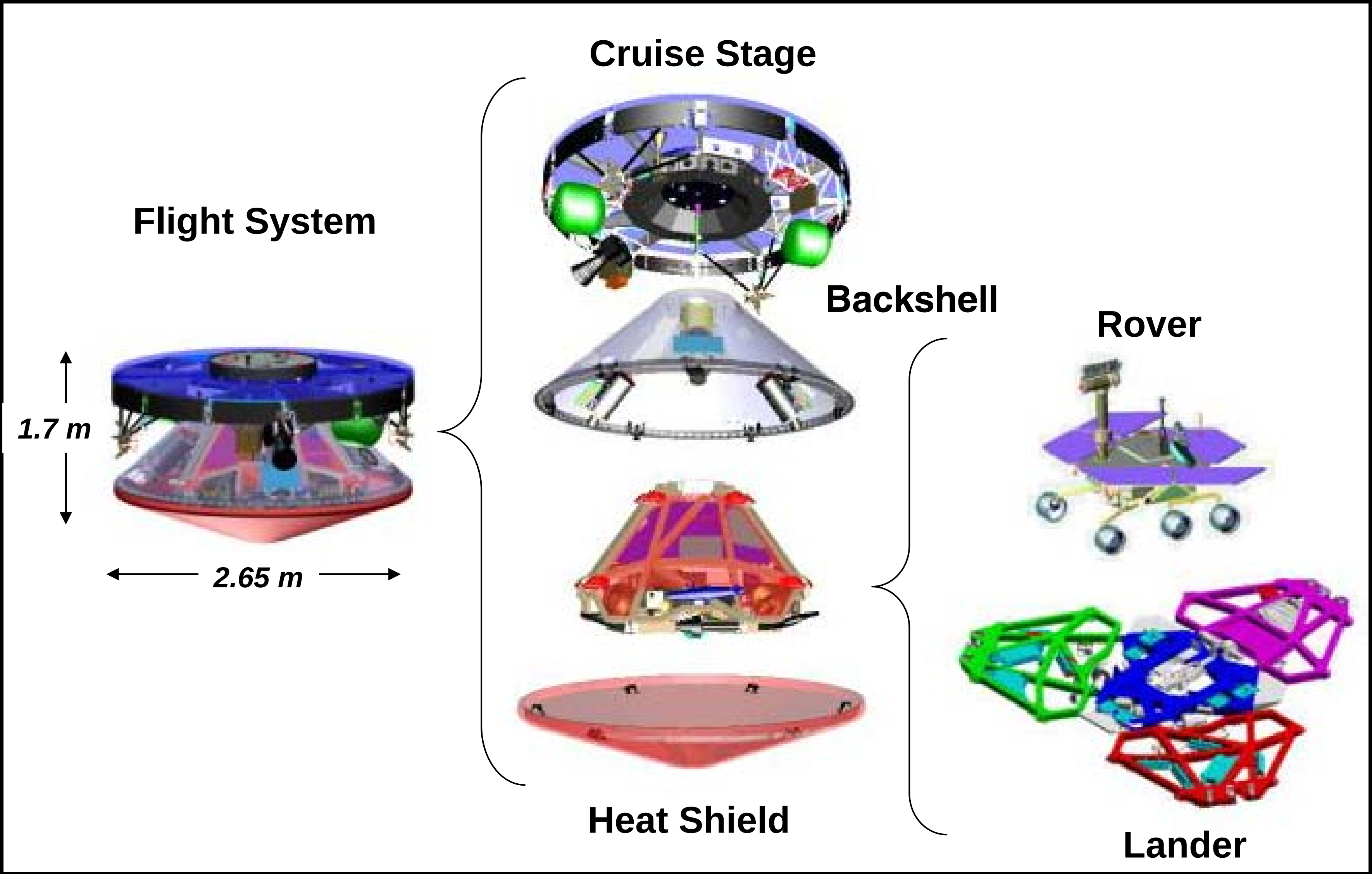
Telecommunication: From Mars to Earth and Back Again



Inside the Rover



Major Spacecraft Elements



Landing Site Selection Criteria

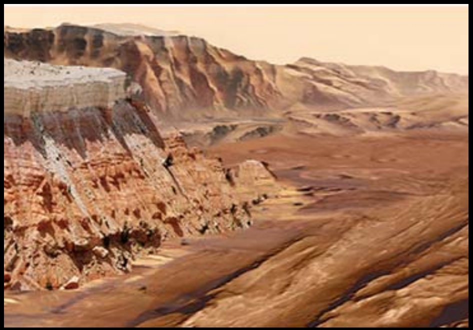
- Both landing sites must be safe (maximum elevation, dust, rock abundance, slopes, winds)
- Selected sites must permit a successful surface mission (e.g. thermal environment, solar energy, terrain characteristics for mobility)
- Selected sites should permit a scientifically successful mission, in which the rovers are capable of addressing the mission science objectives
- Part of the rationale for two rovers is to provide science redundancy by targeting two scientifically different sites (e.g. mineralogical and morphological)

Landing Sites

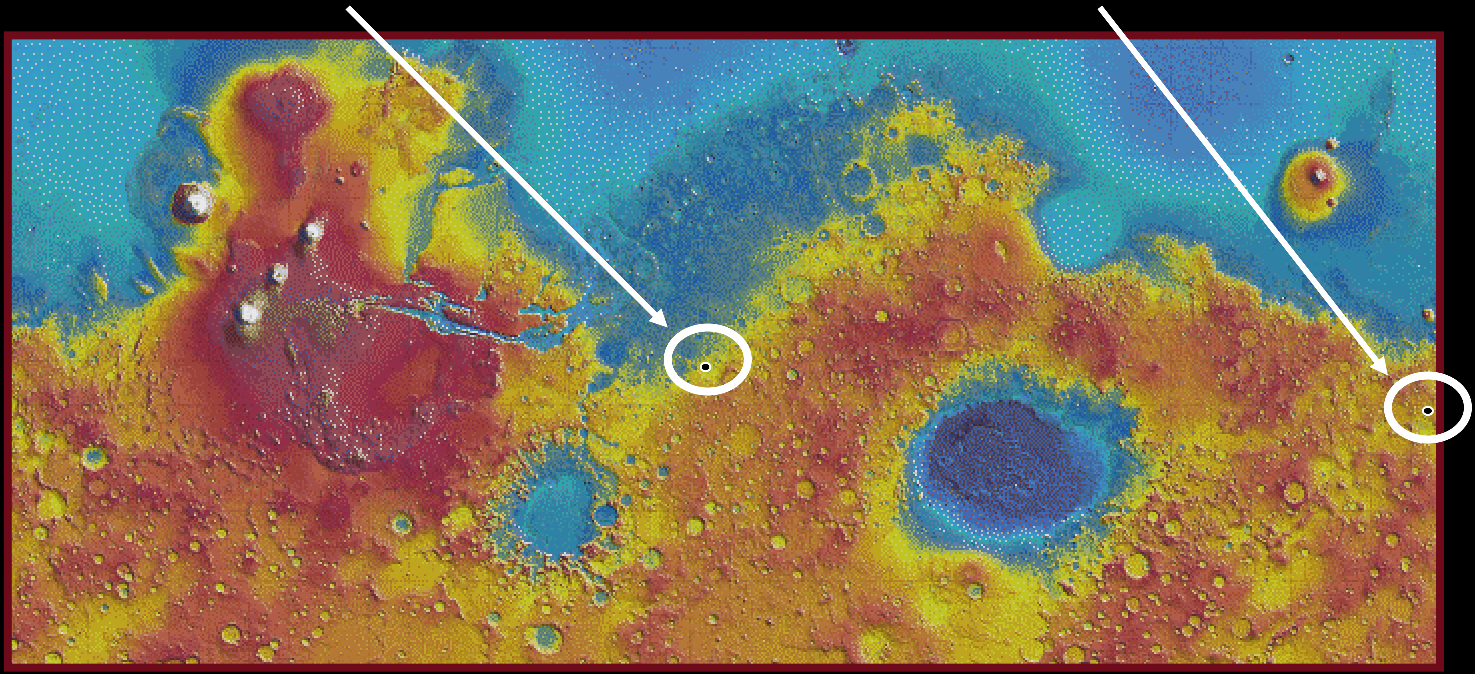
Meridiani Planum

Water-formed hematite?

Gusev Crater

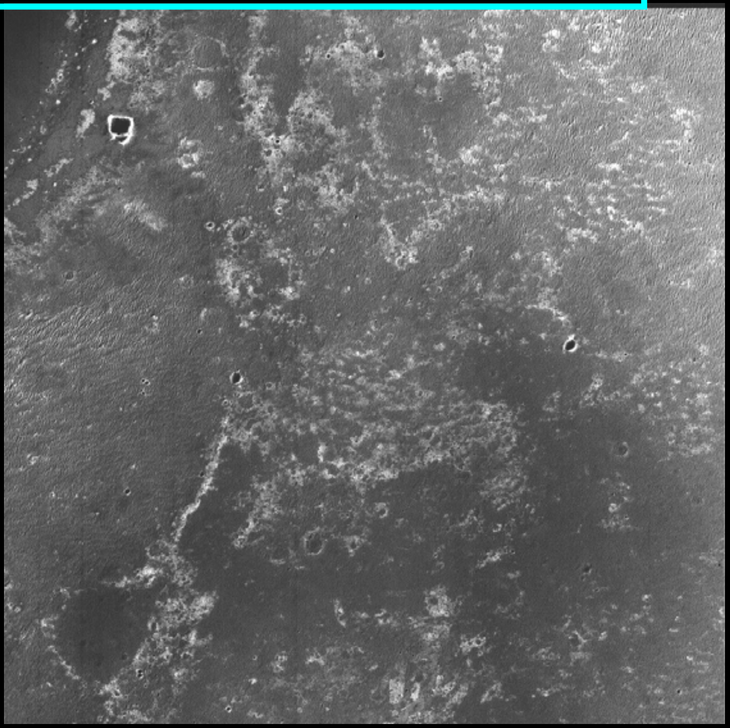


Ancient lake sediments?



Meridiani Planum

<u>Gray hematite</u>: Precipitate from large standing body of water? Precipitate from warm percolating water? Cold ground water? Surface weathering coatings on rocks? High-temperature oxidation of volcanic rock?



Gusev Crater

- Compelling evidence that water ponded in the crater
- Lakebed deposits can preserve substantial evidence of past water-related processes, environmental conditions, and habitability
- Ice-covered lake? Short-lived playa lakes? Muddy debris flows? Ancient highland rocks deposited in the crater?

Challenges for Robotic Planetary Explorers

- Robots operate in a completely unstructured and unknown terrain environments
- Orbital imagery does not yet provide fine scale details required for in-situ exploration (don't know what is just around the corner)
- Rovers are autonomous receiving daily instructions in the Martian morning and tell us what happened in the Martian afternoon
  - Rovers are not "joy-sticked" or "teleoperated"
  - Two way light time precludes this type of operation
- Heavy use of on-board sensor feedback (vision, inertial, etc) for autonomous EDL, rover driving, manipulation

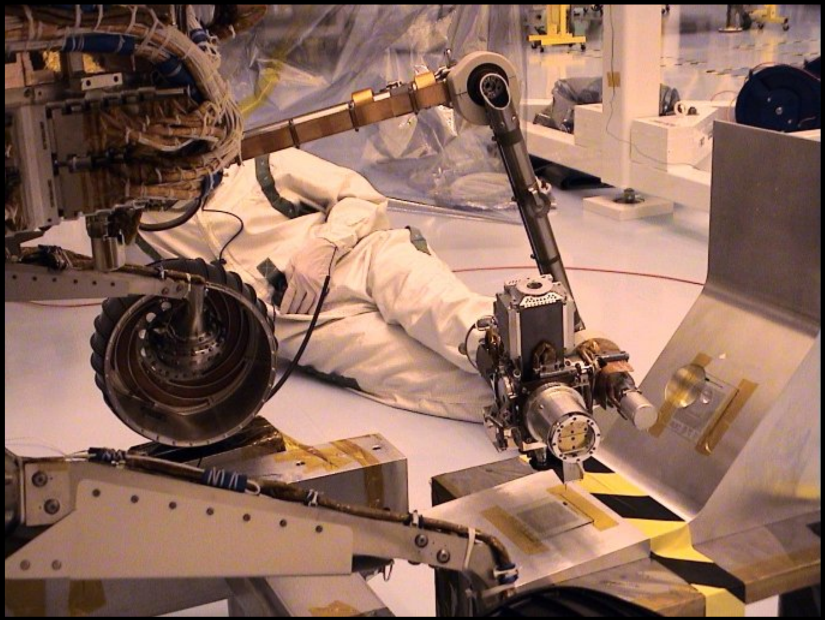
Robotic Functions

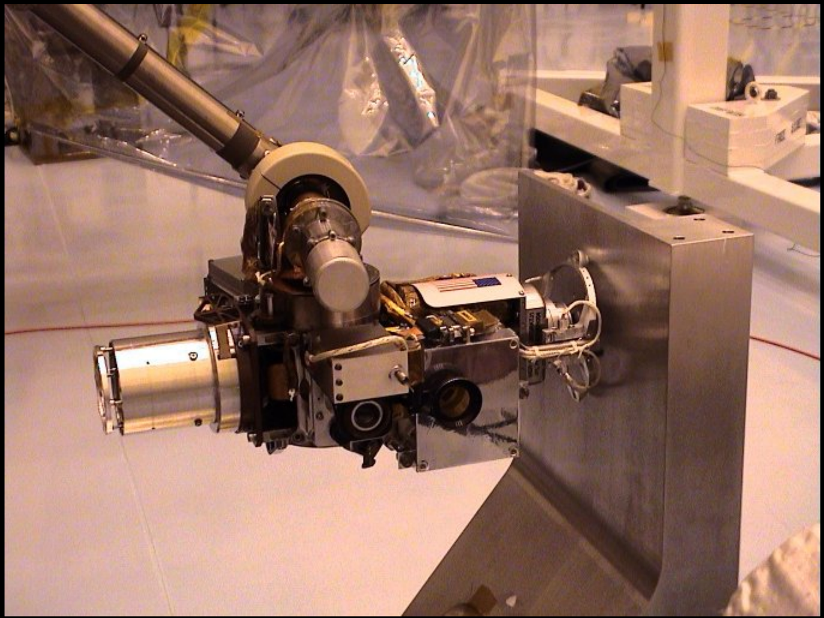
- Remote Sensing
  - Terrain classification and remote spectroscopy in the visible and near-infrared
- Mobility and Navigation
  - Rover localization using sensor fusion (wheel odometry, inertial measurements, vision, etc)
  - Autonomous sensor-based rover navigation including hazard detection and hazard avoidance
- In-situ Instrument Placement
  - Target selection via stereo range maps (3D position and surface normals)
  - Proximity sensing
  - Collision detection and fault protection

The Instrument Positioning System (IPS)

IPS Functions

- Place the APXS, MB and MI on rock and soil targets
- Place and hold the RAT on rock targets during rock grinding activities
- Place the APXS and MB on rover-mounted targets (magnet experiment and MB calibration target)



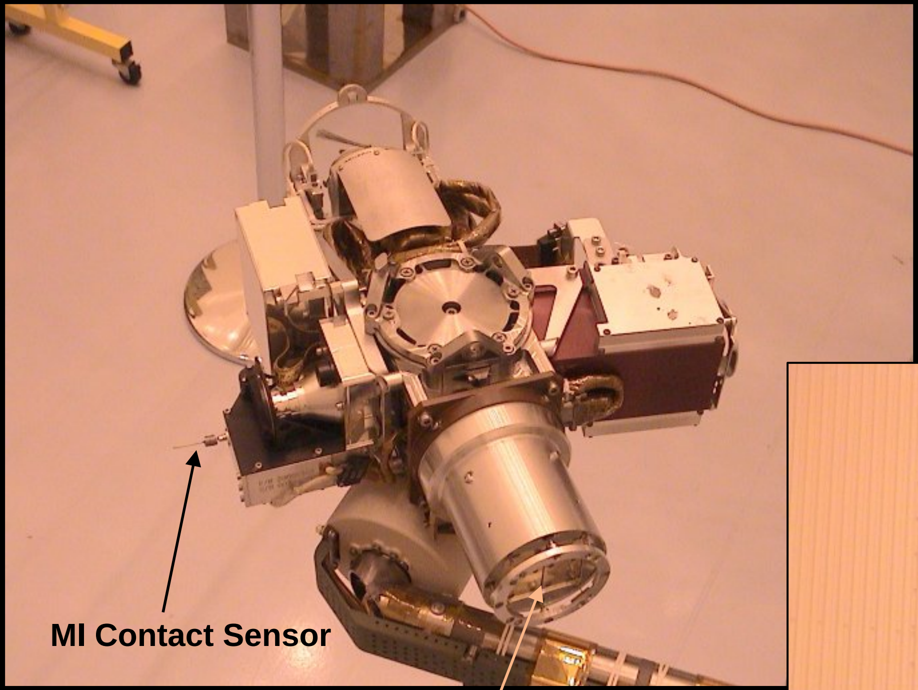


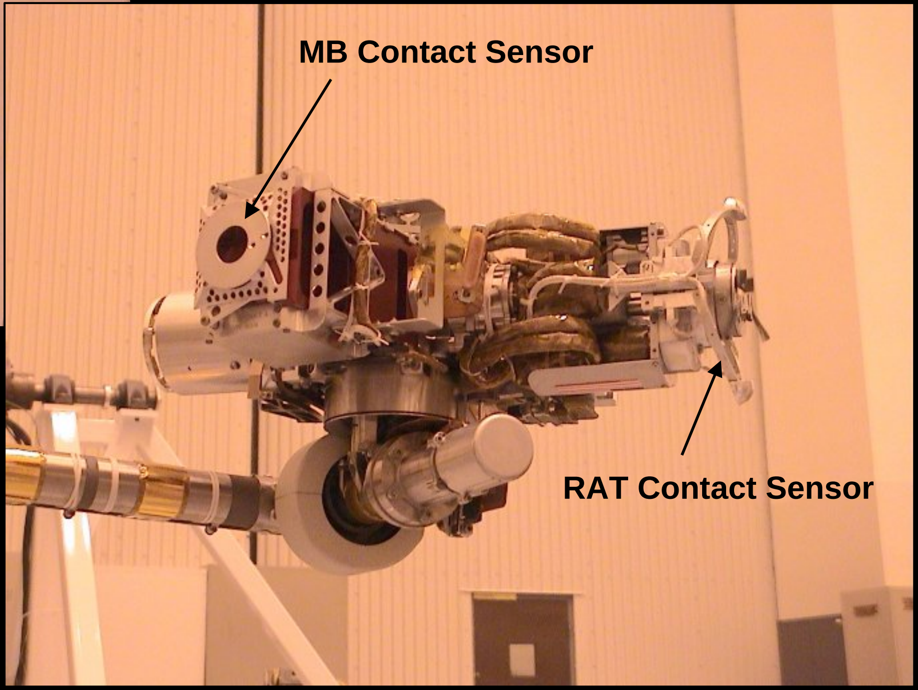
IPS Requirements Summary

- Initially place the in-situ instruments (MI, APXS, MB, RAT) to within 10 mm in position and 10 degrees in orientation relative to rock and soil target surfaces including appropriate actuation of each instrument's contact sensors
  - Achieved 4.2 mm mean (9 mm 3σ), 0.5 deg mean (1.5 deg 3σ)
- Repeatable placement of the in-situ instruments to within 4 mm in position and 3 degrees in orientation relative to rock and soil target surfaces
  - Achieved 0.3 mm mean (1.3 mm 3σ), 0.3 deg mean (1.2 deg 3σ)
- Incrementally position the MI by the minimal controllable motion of 2 mm ± 1 mm
  - Achieved with sub-mm minimum motion
- Place the in-situ instruments any time during the Martian diurnal cycle

Proximity Sensing

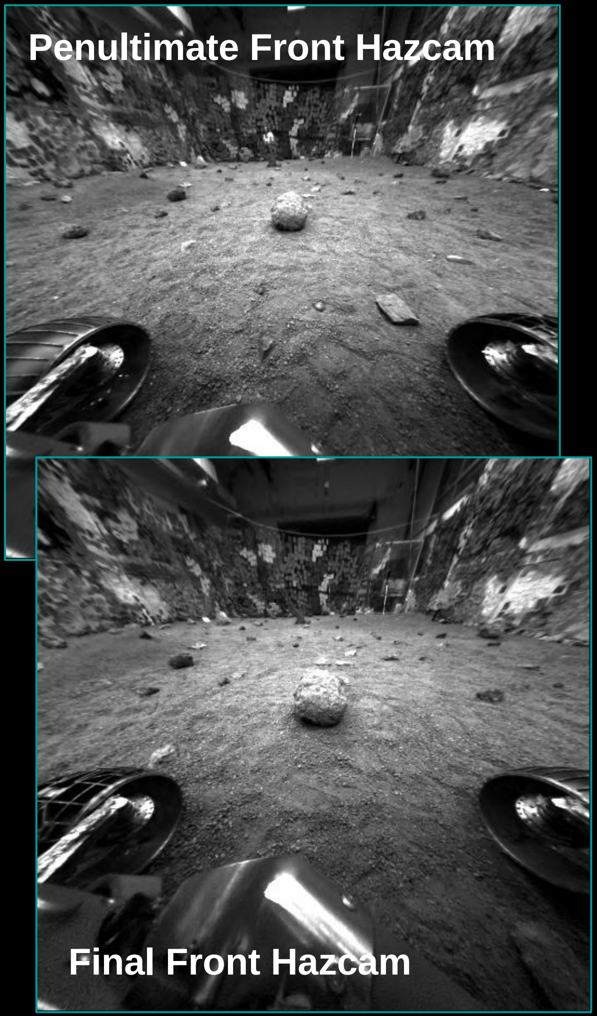
- All instrument contact sensors are dual redundant with the exception of the APXS dust doors and contact sensor





Instrument Placement Ops

- At end of rover drive, penultimate and final front Hazcam images are acquired
- From these stereo images, range maps of the terrain within the IDD workspace are computed
  – Range and surface normals (x, y, z, n_x, n_y, n_z) are calculated for every image pixel
  – Every range point is tested to see if the point is reachable by each of the instruments
  – The reachable points are then tested in terms of detecting collisions between the IDD, rover, instruments and the environment
  – The resulting map is the so-called Reachability Map
  – 3D terrain meshes are also generated based on the stereo range maps

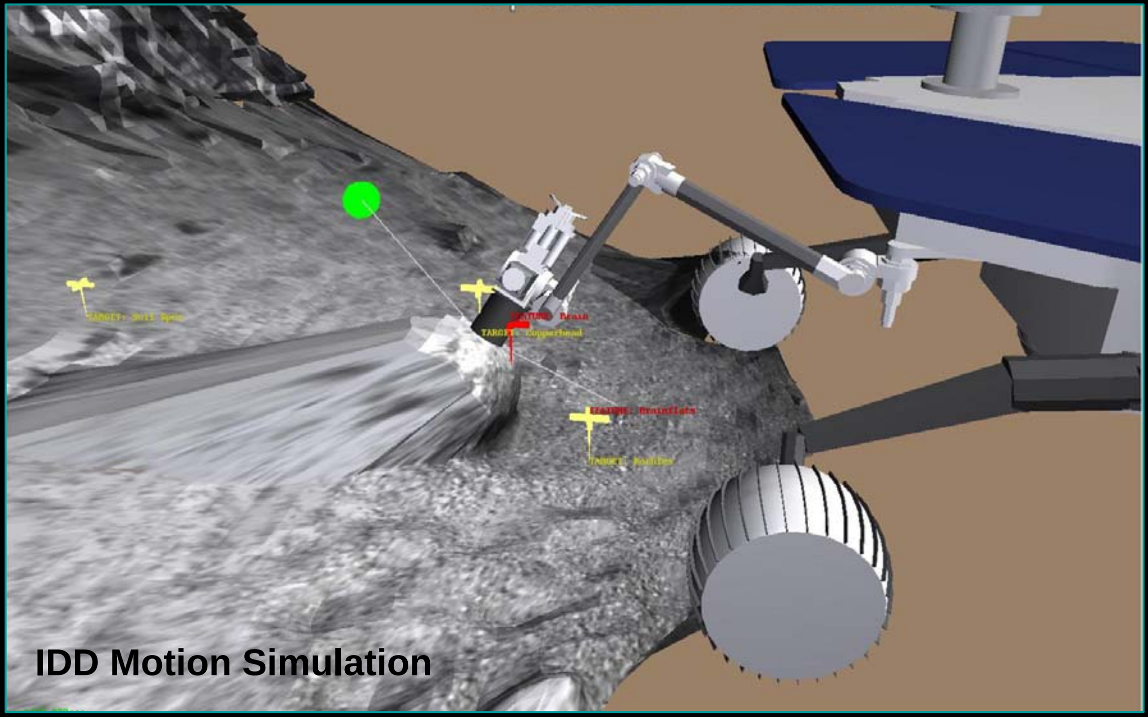


Instrument Placement Ops

- Science-driven instrument placement targets are then selected from the locations within the reachability map

Instrument Placement Ops

- Detailed IDD motion planning and sequence development is accomplished within a high fidelity simulation environment
  - 3D modeling of the IDD, rover, instruments and terrain
  - Simulations of IDD motion and sequence execution are driven flight software including terrain collision detection

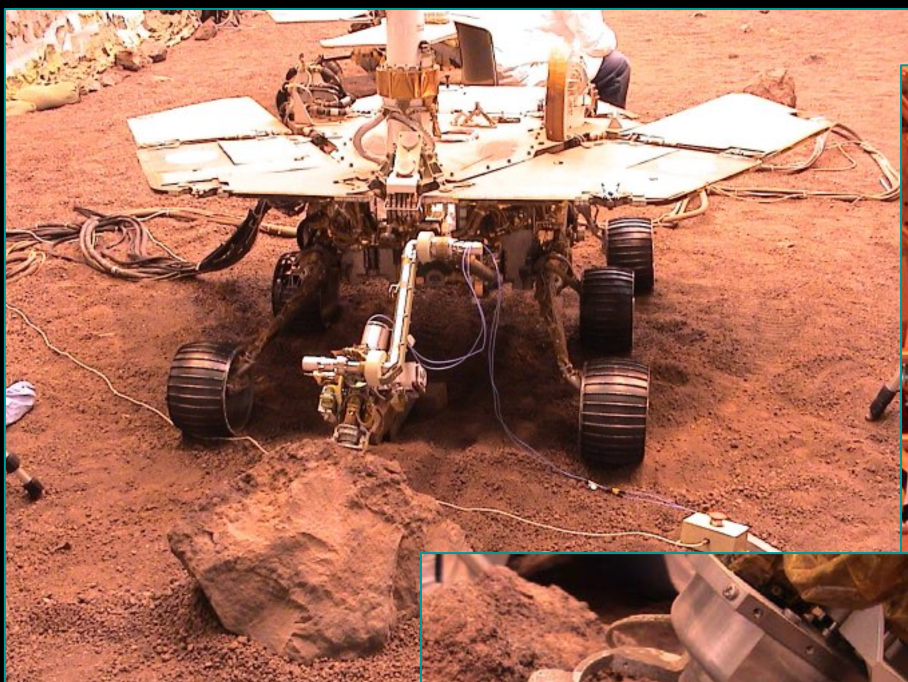


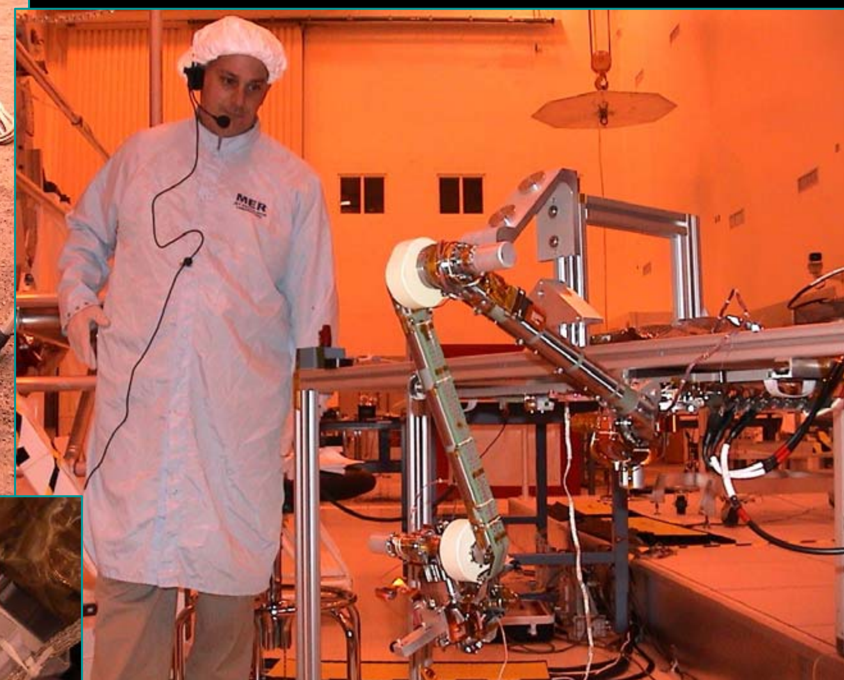
IDD Software Functions

- High-level commanding for operations such as un-stowing and stowing the IDD
- Commanding within Cartesian-space and/or joint-space
- Deflection (droop) compensation
- Collision detection between IDD, rover and instruments (no on-board terrain collision detection)
- IDD inverse kinematics computed based on current pose (no automatic pose configuration changes are allowed, e.g., elbow up to elbow down)
- Motor current limiting based on effects such as temperature and IDD pose
- Four motion modes based on the context of the instrument placement activity (e.g., free-space motion, guarded motion, pre-load motion, retraction motion)

Testing, Testing, Testing

- Testing occurred at sub-system, system and operations level for both flight and Engineering Model (EM) units



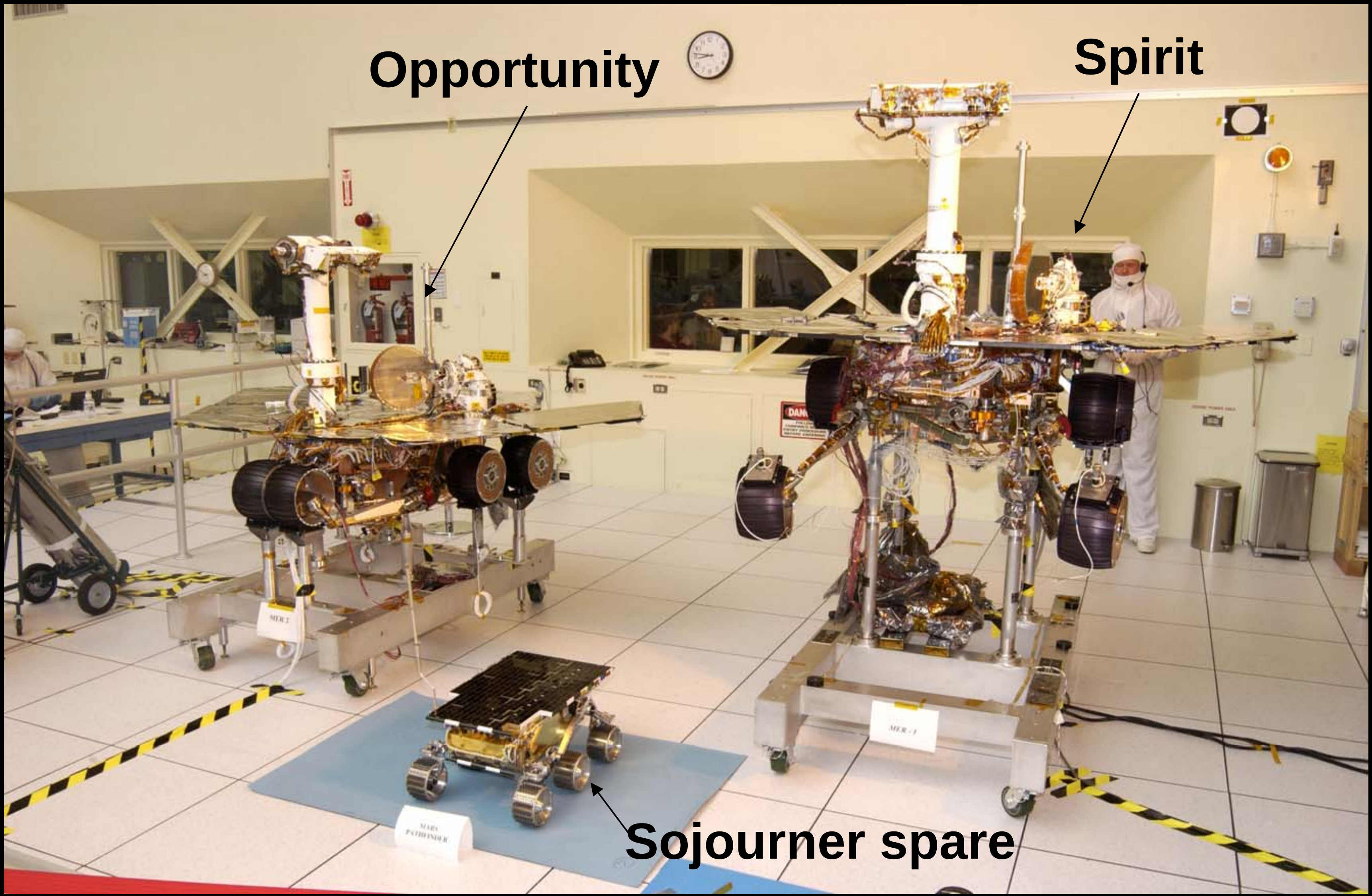


Testing, Testing, Testing

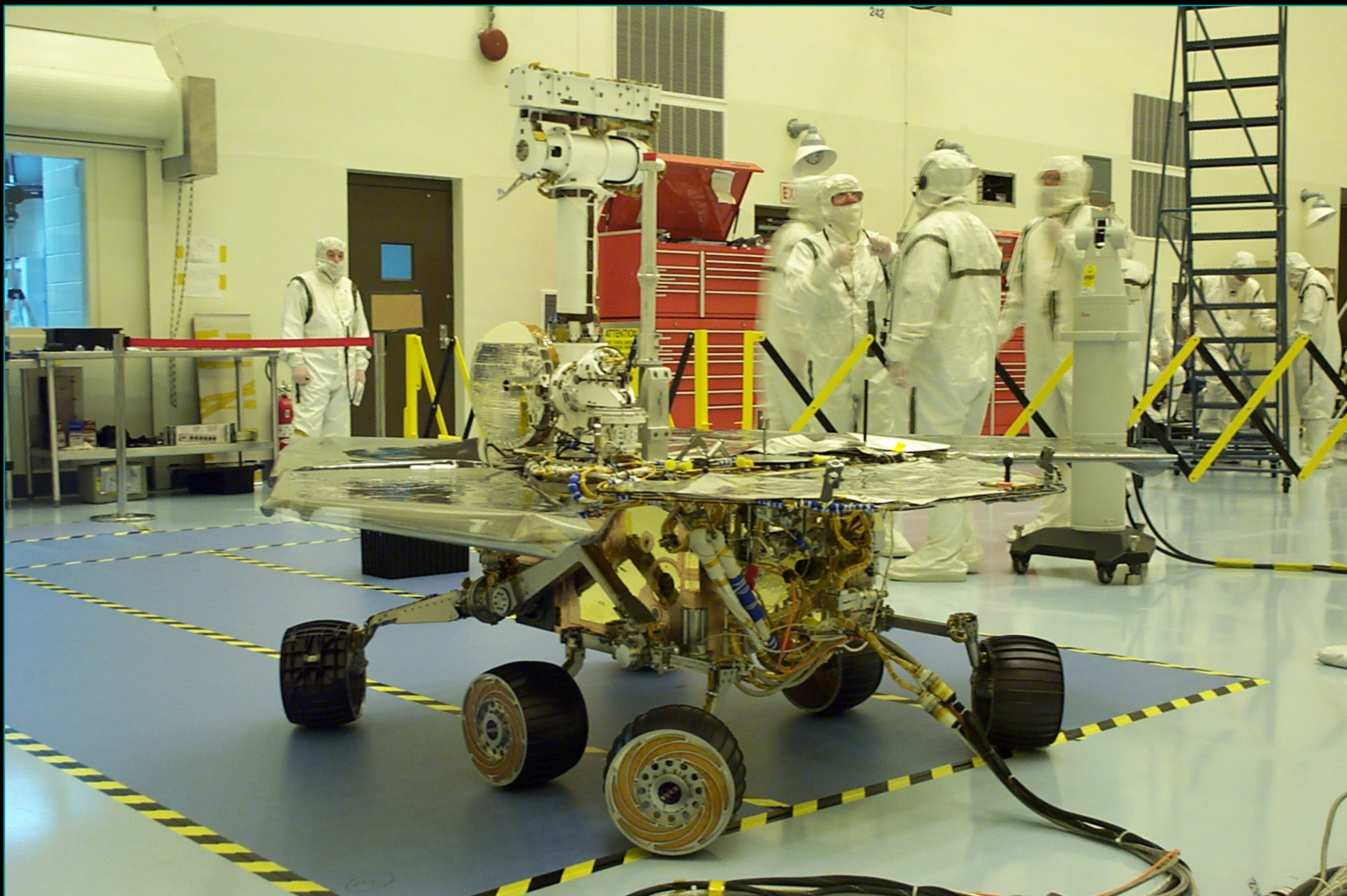
- Operational Readiness Tests

Building the Rovers

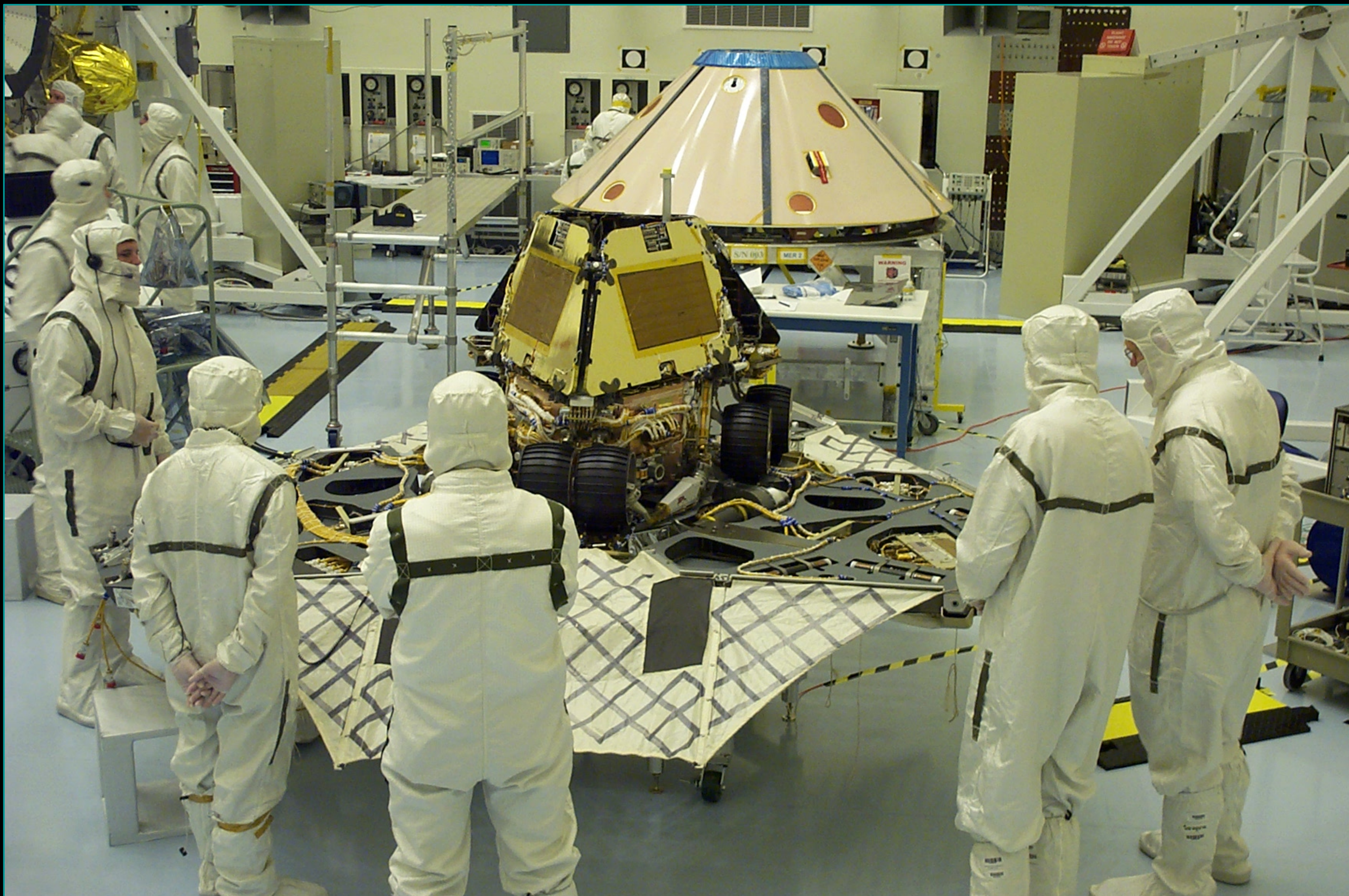
Rover Family Photo



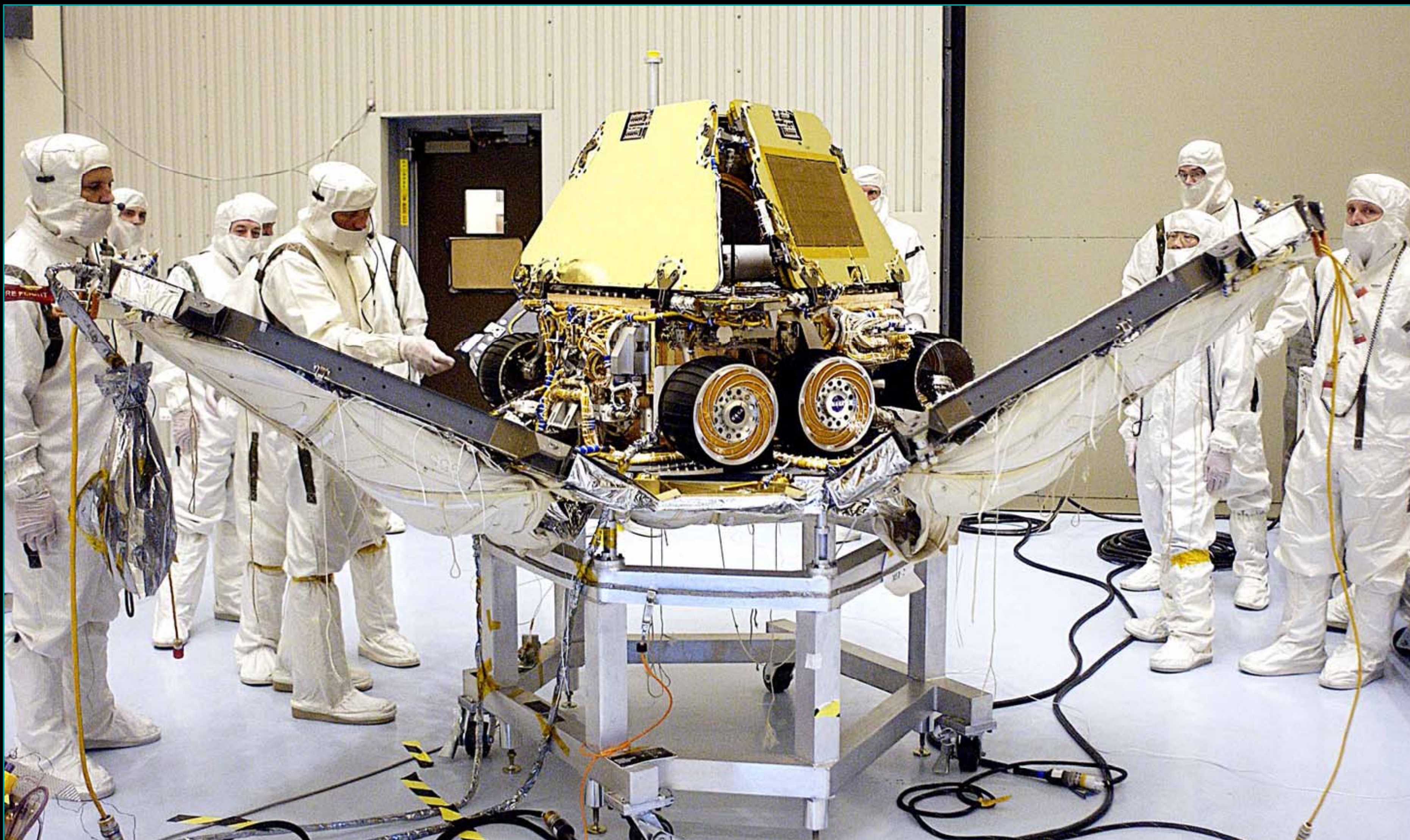
Spirit Driving Tests



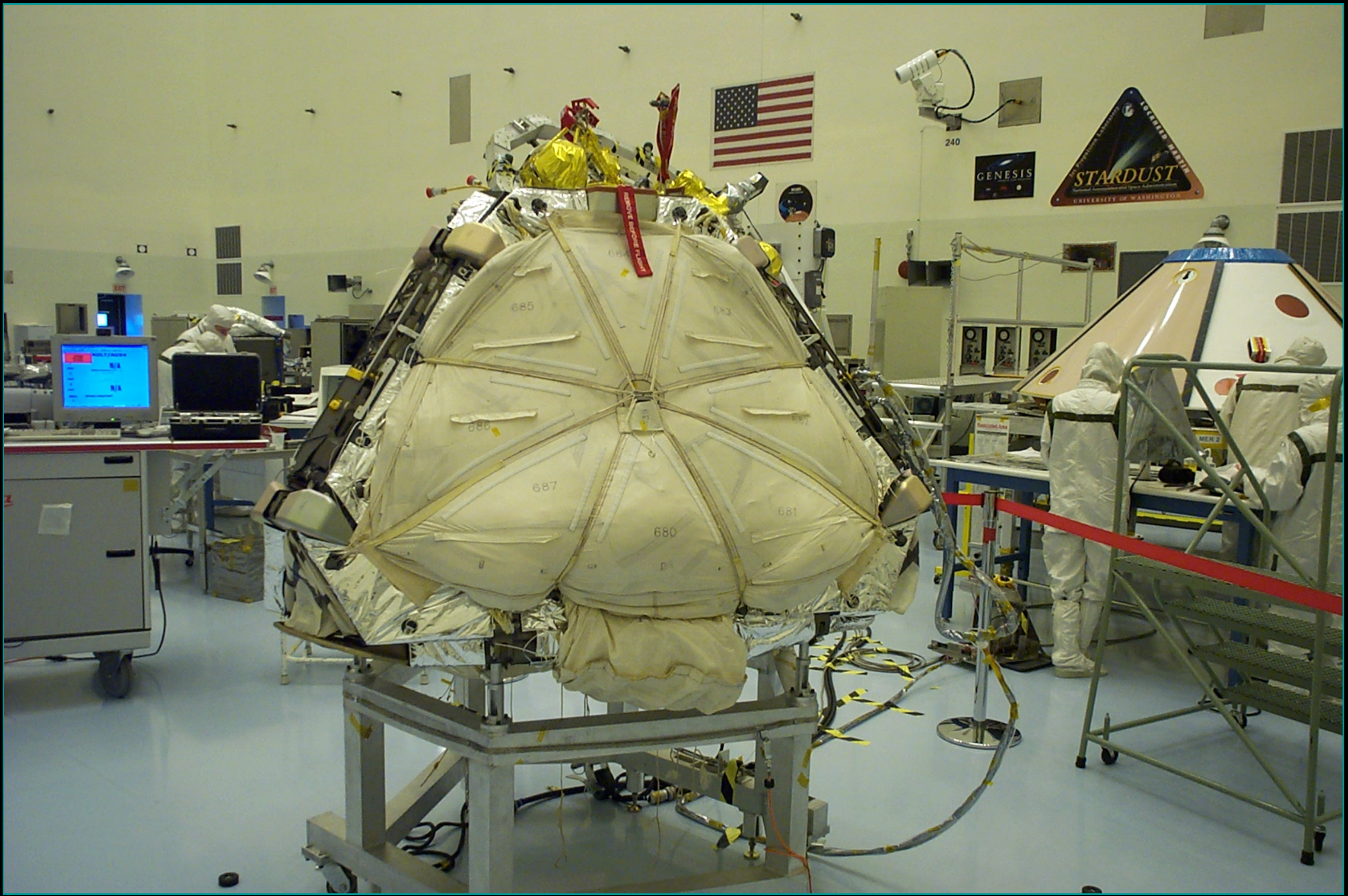
Stowed Rover and Lander



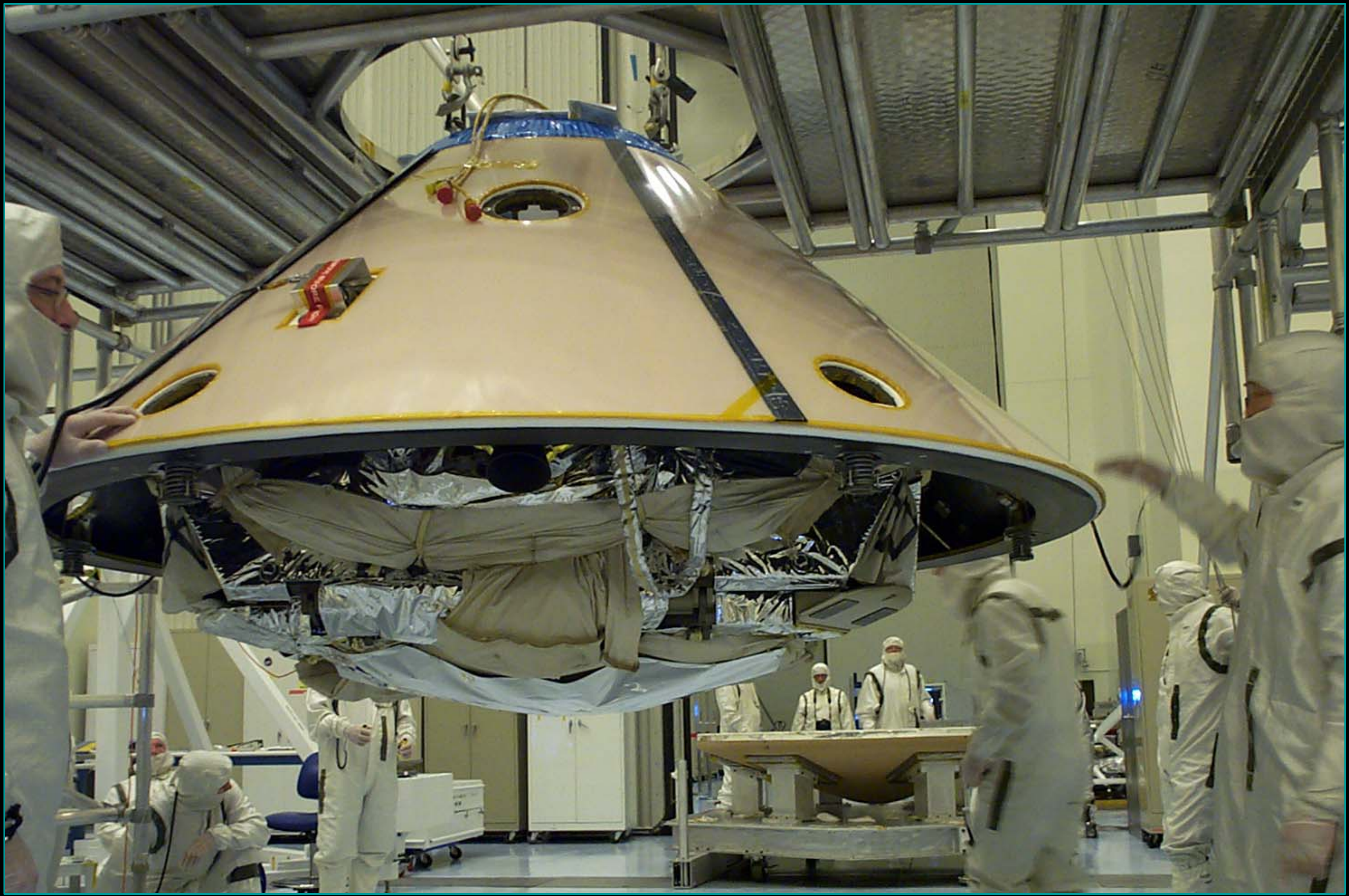
Stowing the Lander



Integrated Lander



Lander in Backshell



Launch/Cruise Configuration

On the Third Stage

In the Launch Fairing

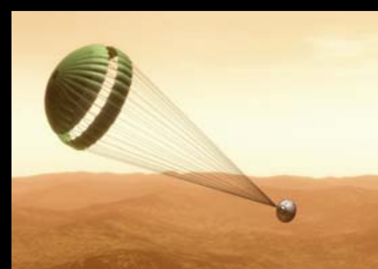
The Mission

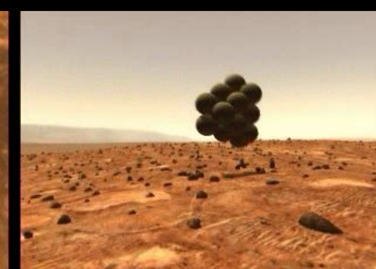
The Three Challenging Mission Phases

Launch & Cruise

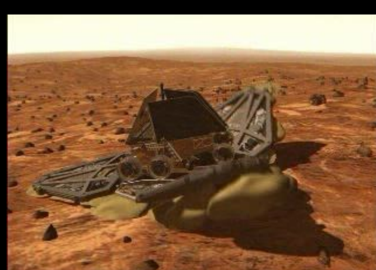
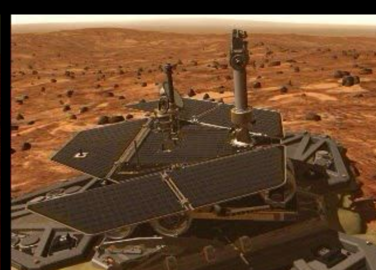
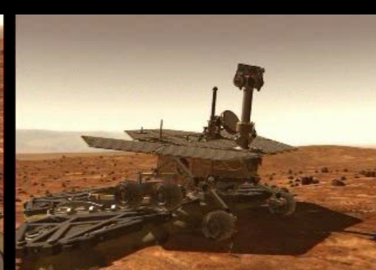



Entry, Descent & Landing

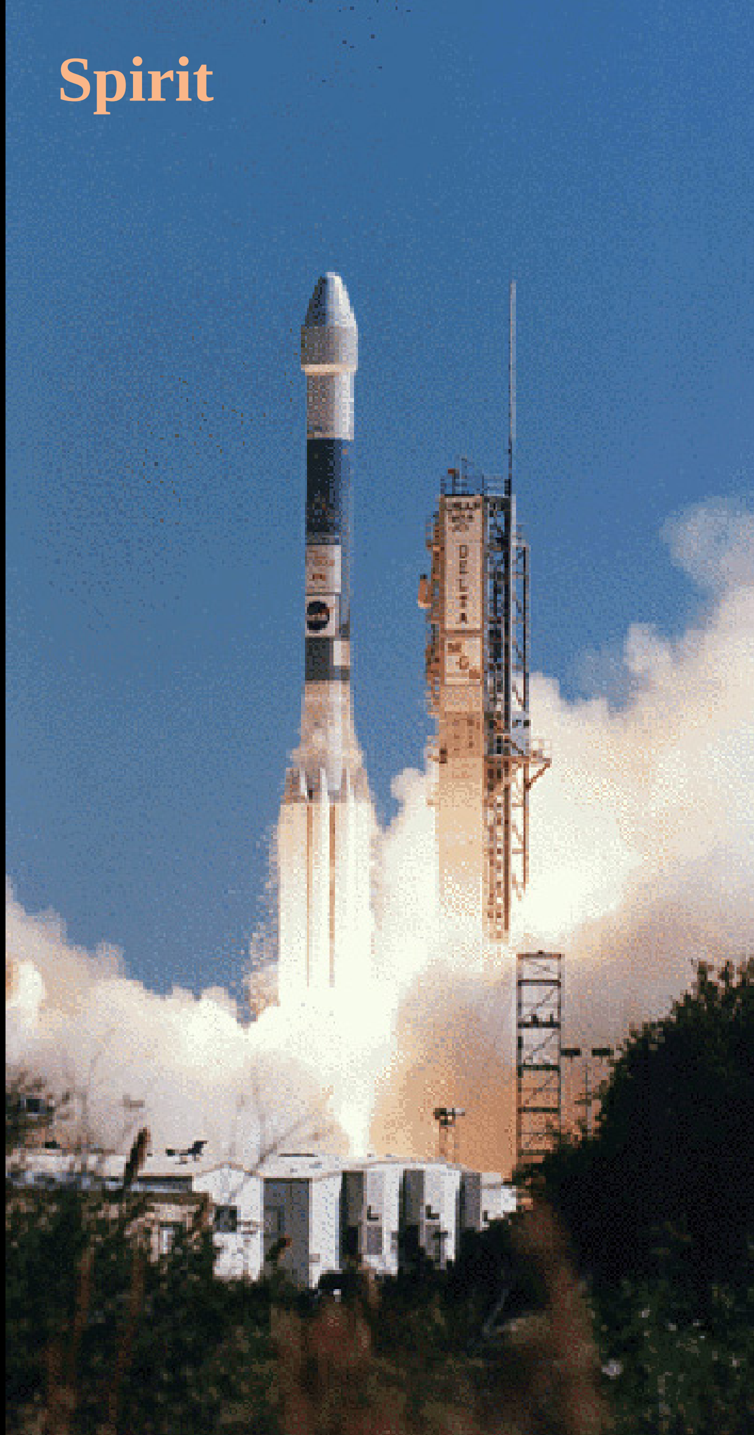



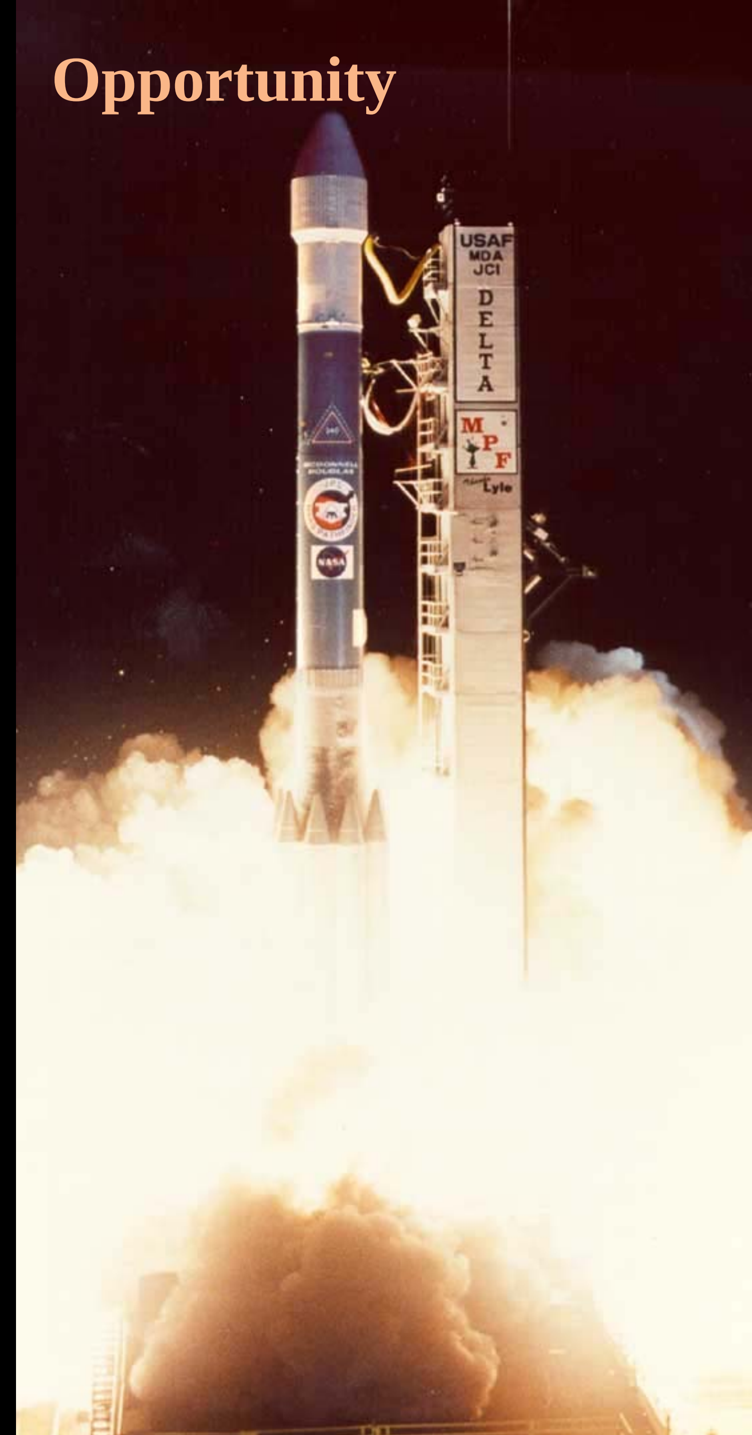


Egress & Surface Operations

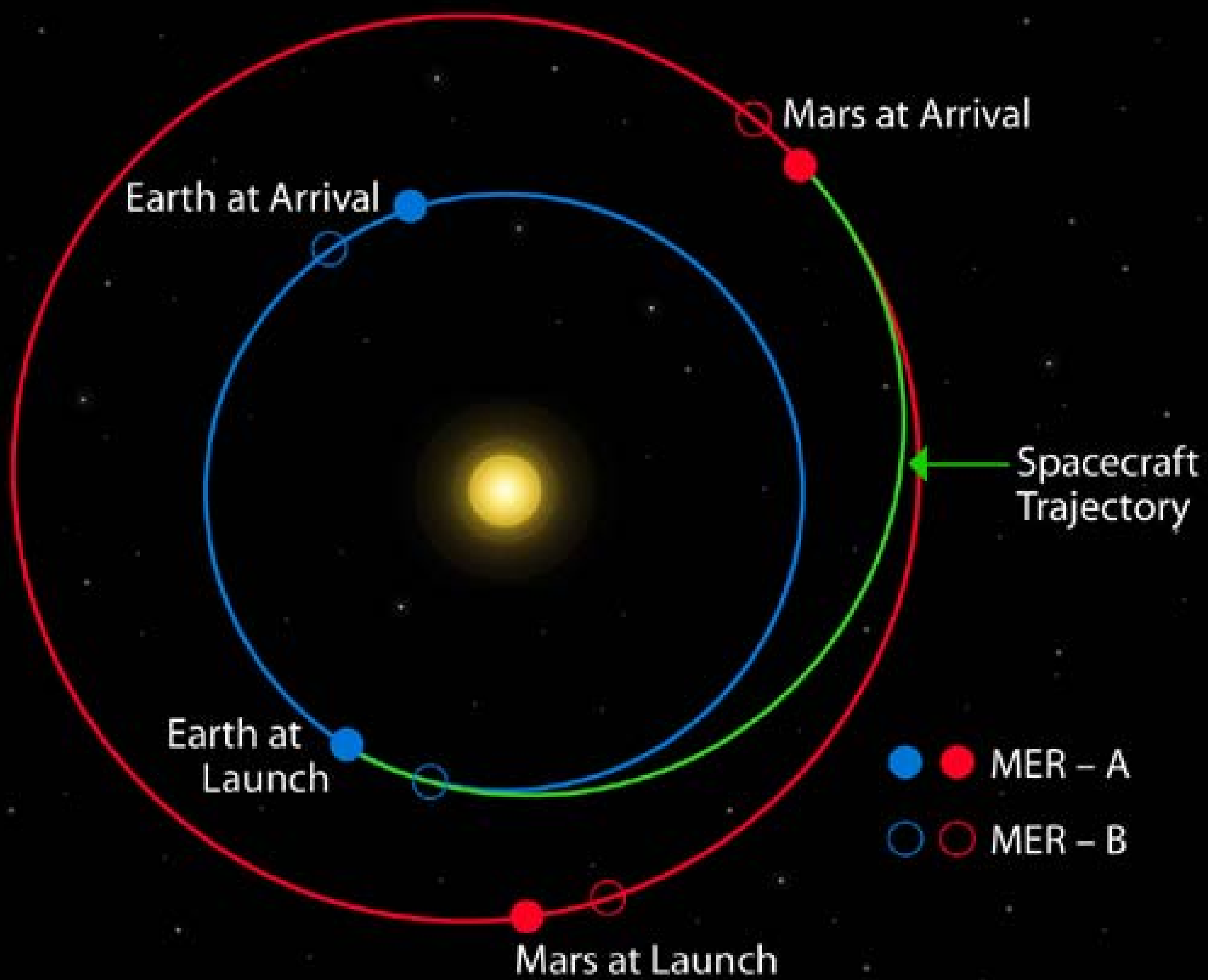





Images From Mission Animation by Dan Maas


Spirit


Opportunity
USAF
MDA
JCI
DELTA
MPF
NASA

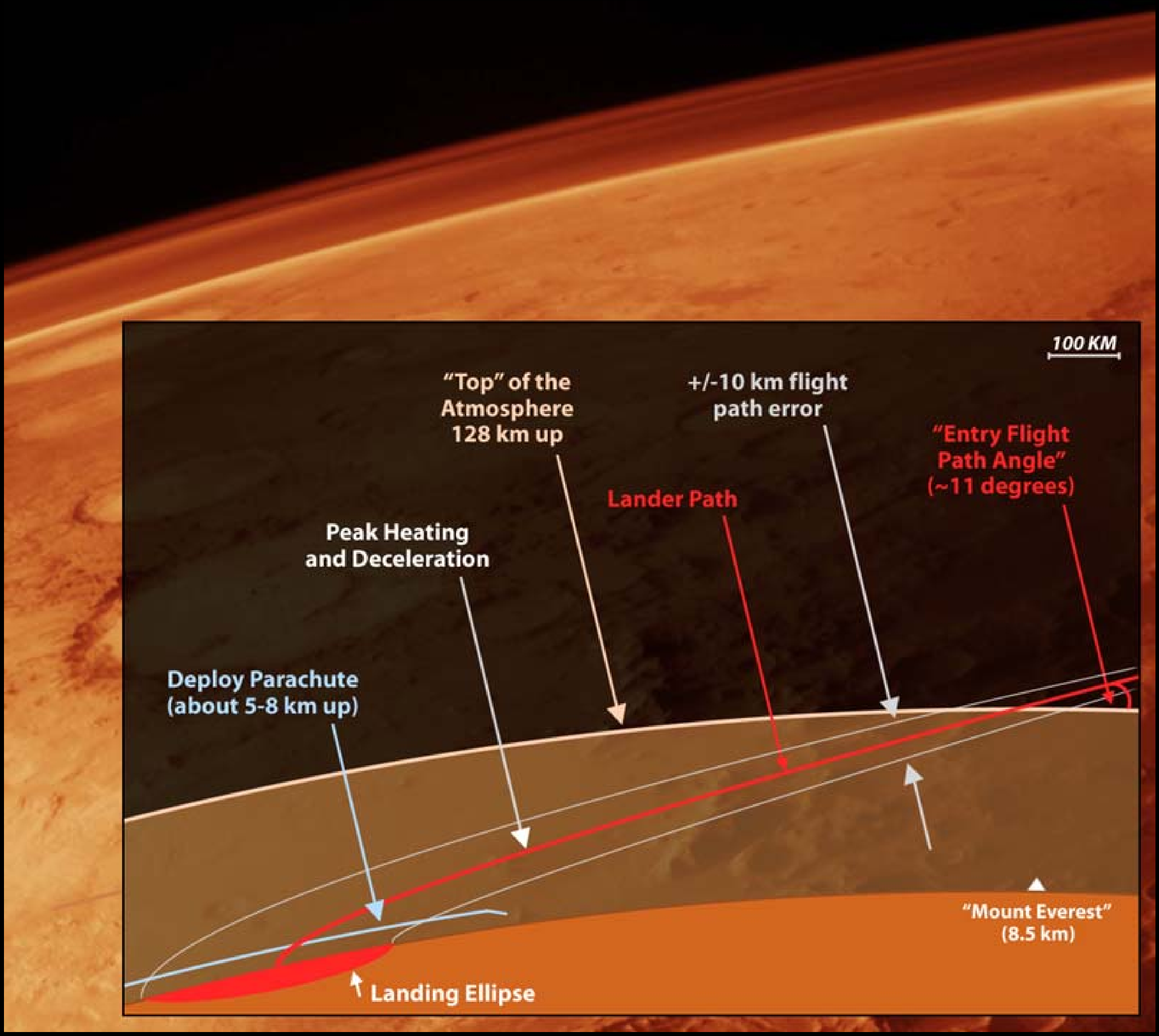
The Cruise Trajectory



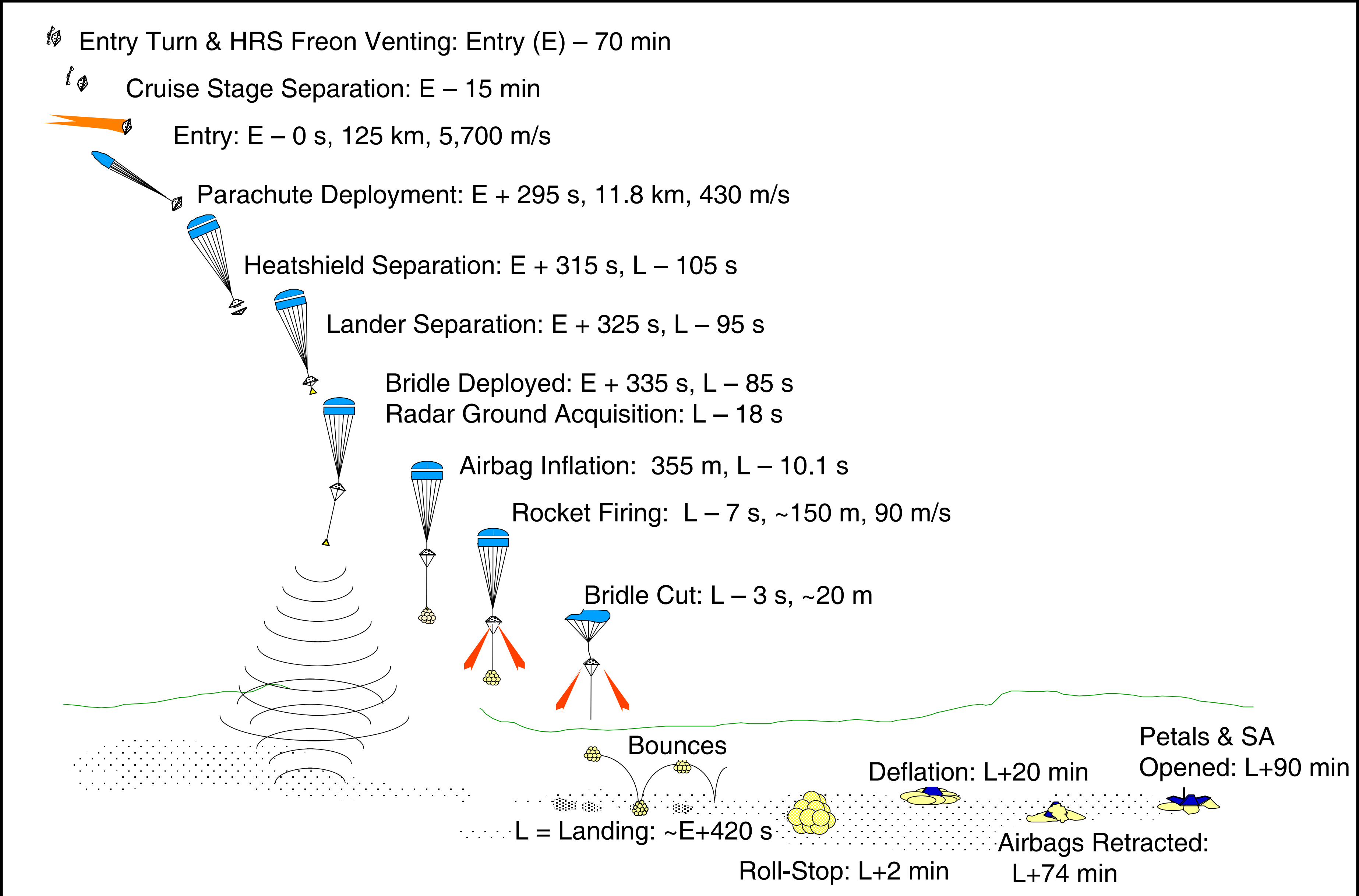
Entry, Descent and Landing

Any steeper and you get to the ground too fast!

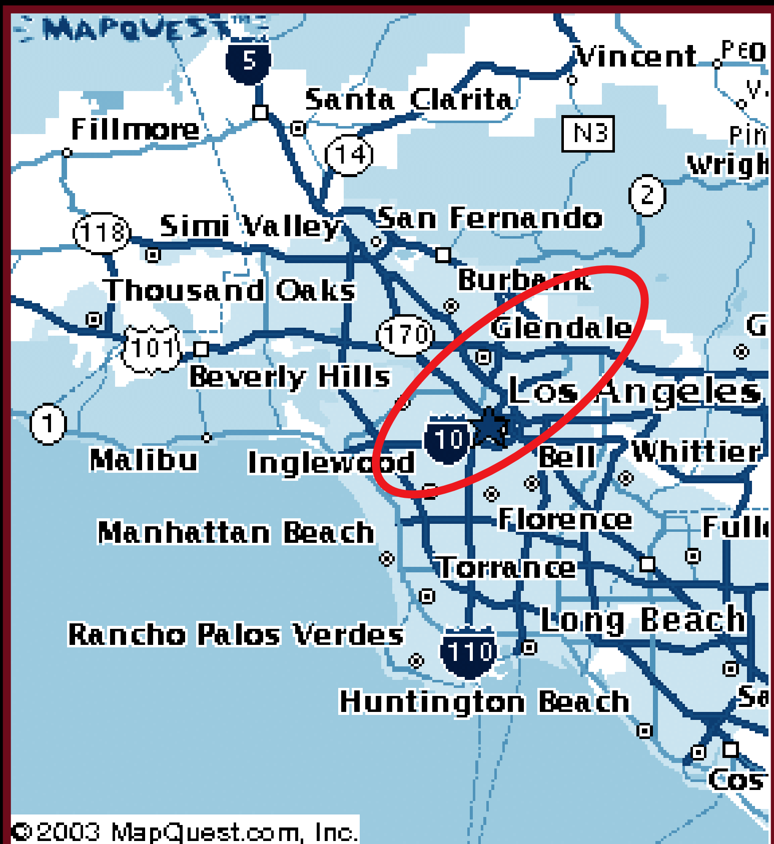
Any shallower and you “skip out” back into space!

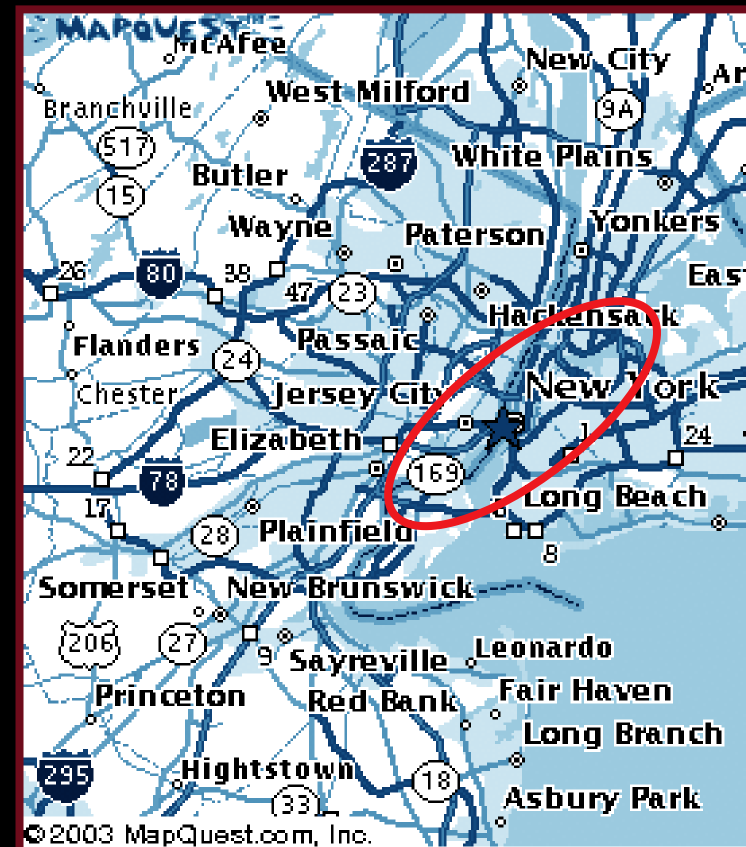


Entry, Descent and Landing



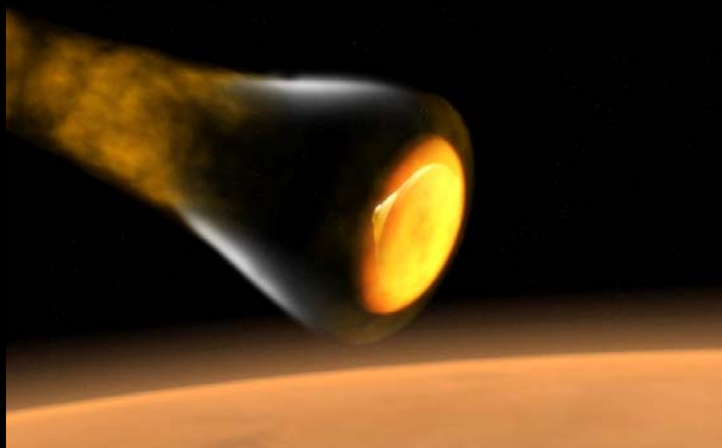
The Landing Ellipse



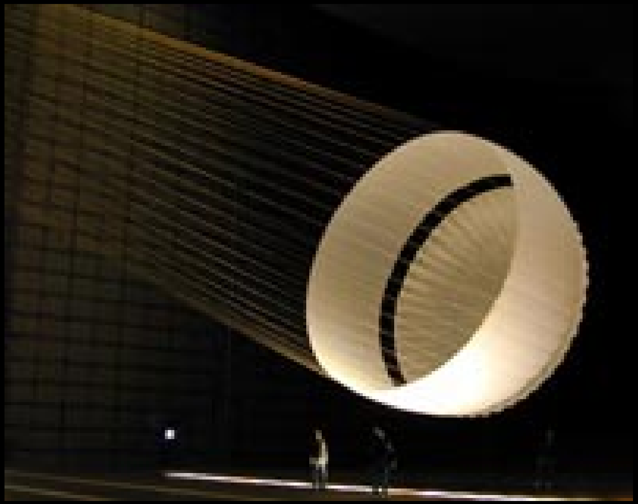
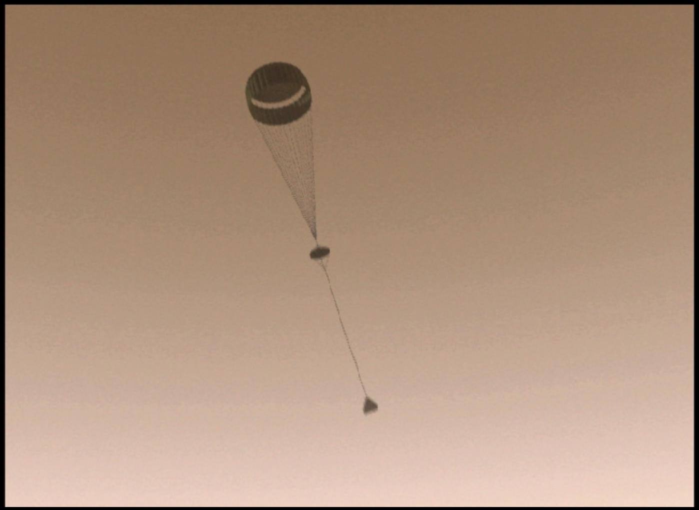
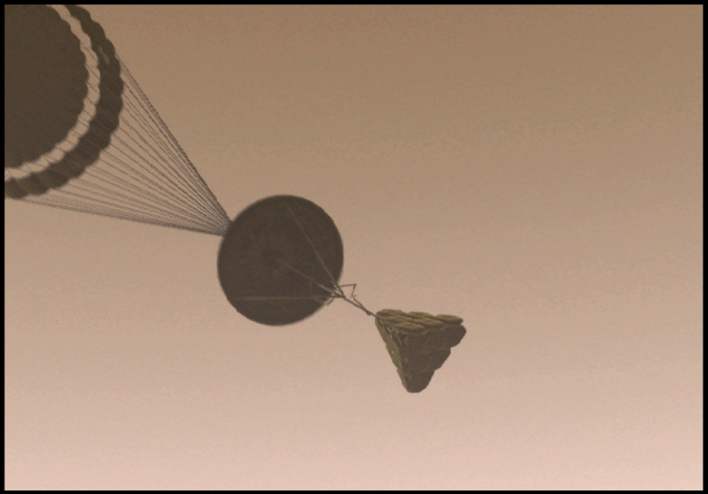
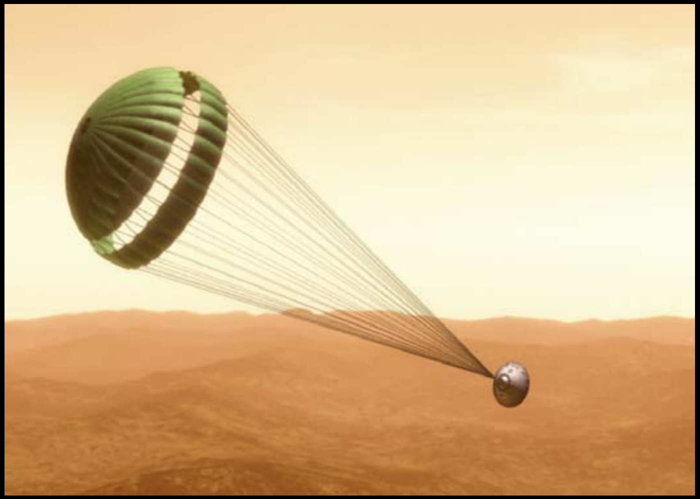


Only 100 X 20 Kilometers

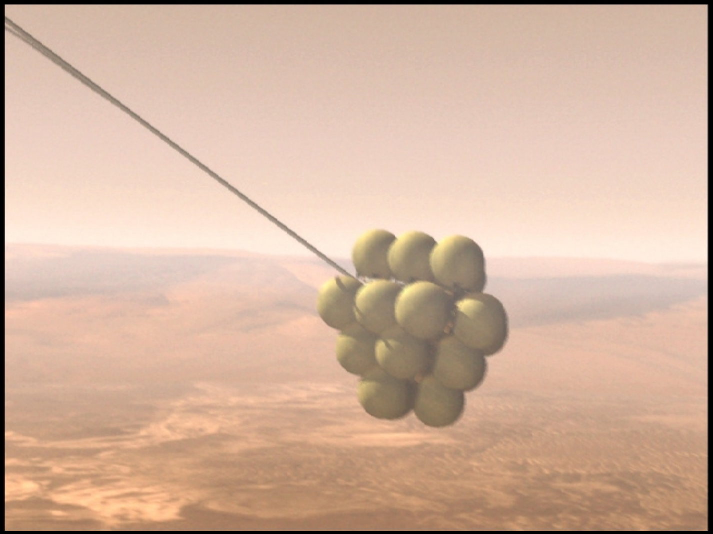
Heatshield takes out 90% of the energy

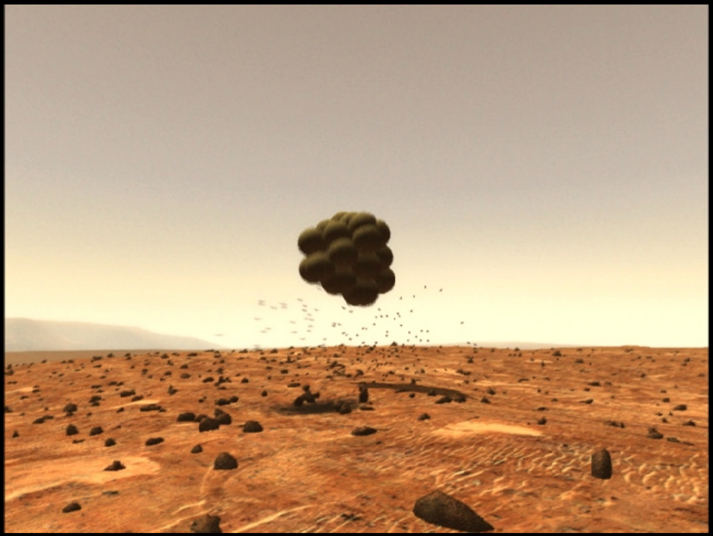


Parachutes open at Mach 1.3 and slow the lander to 200 mph

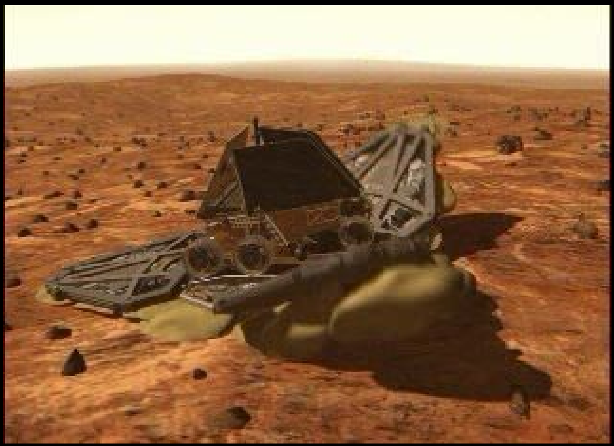
Rockets and airbags do the rest

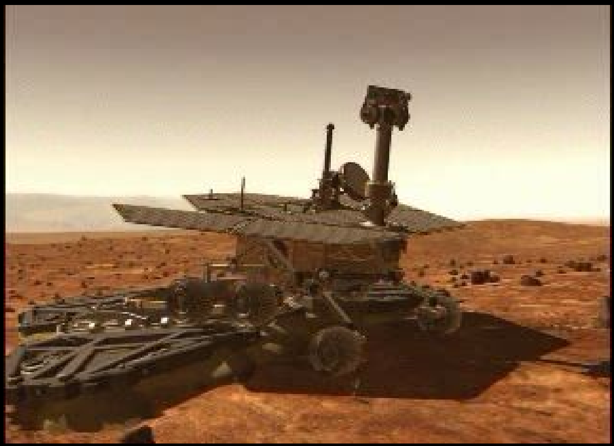





Once safe on the surface, it's time to:

Open up the lander,
Unfold the rover,
Call home,
Look around, and
Get moving!

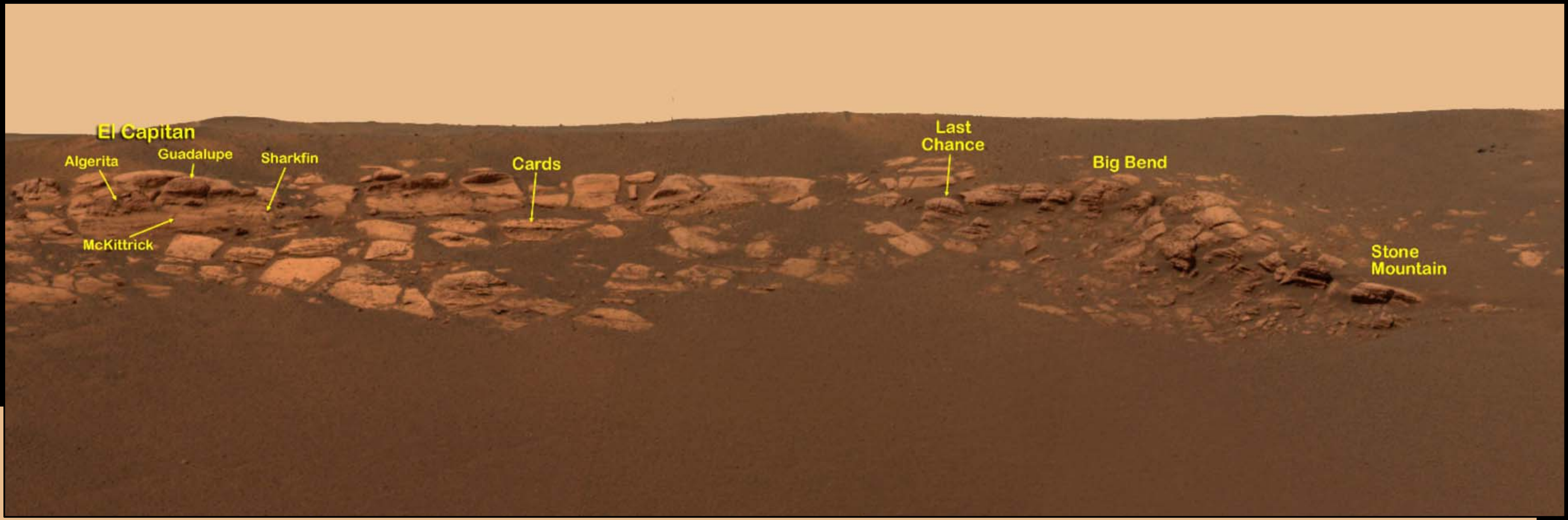




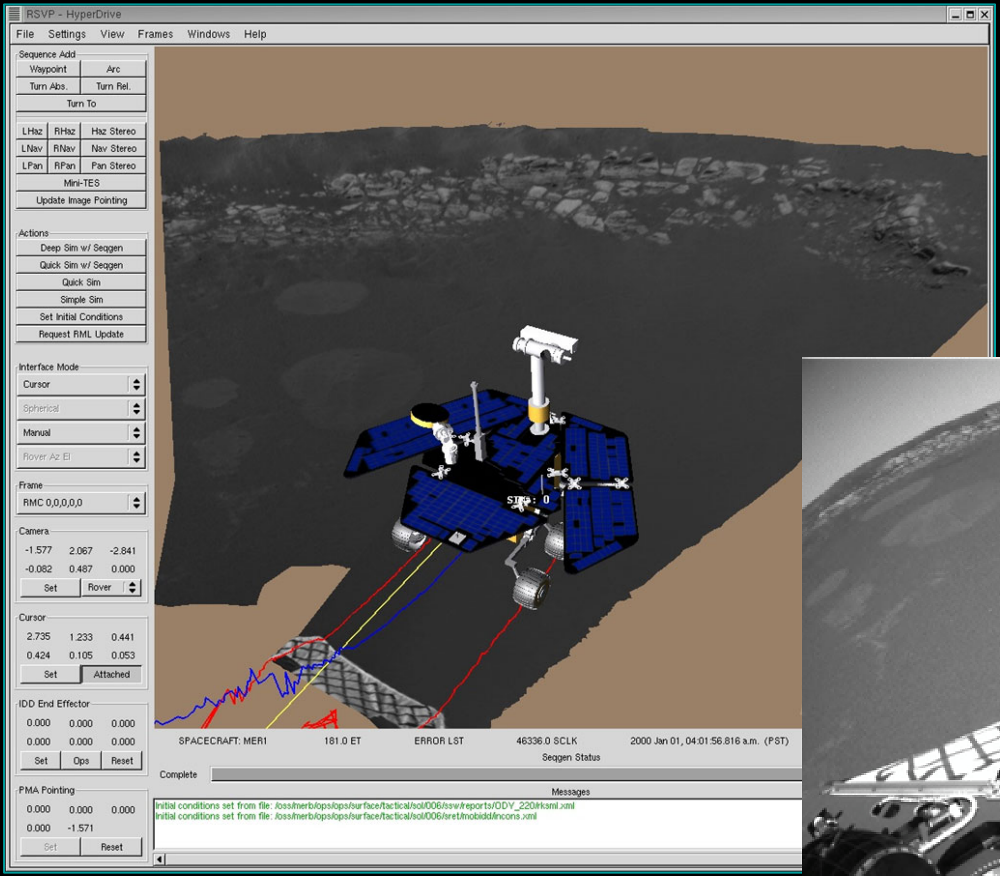
MER Animation

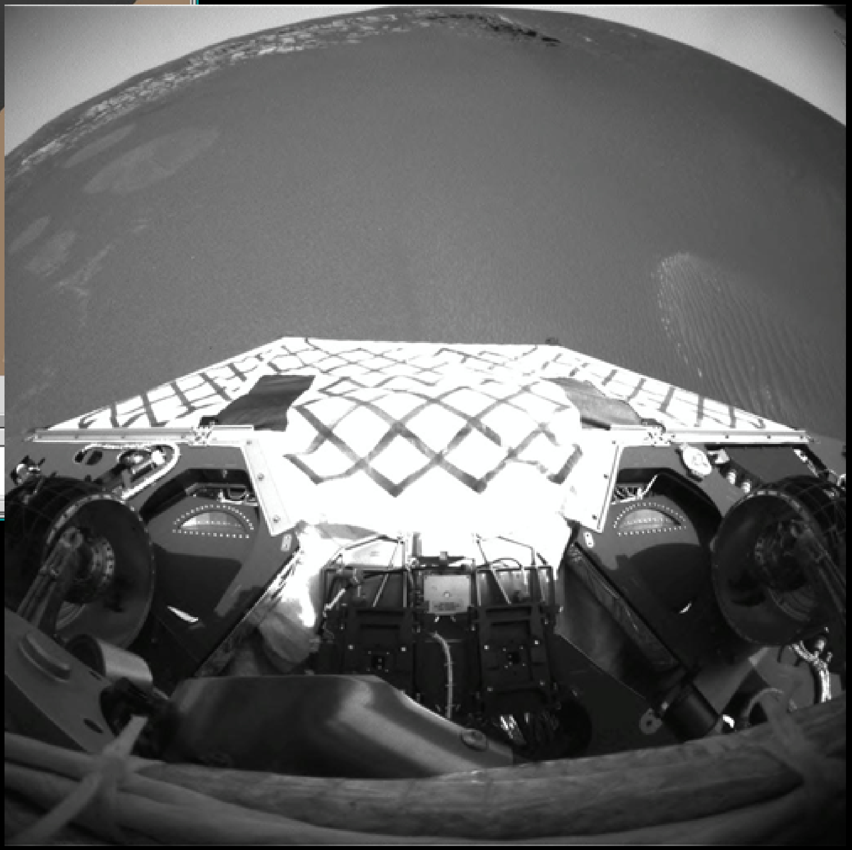
Opportunity Landing Day

Eagle Crater's Outcrop

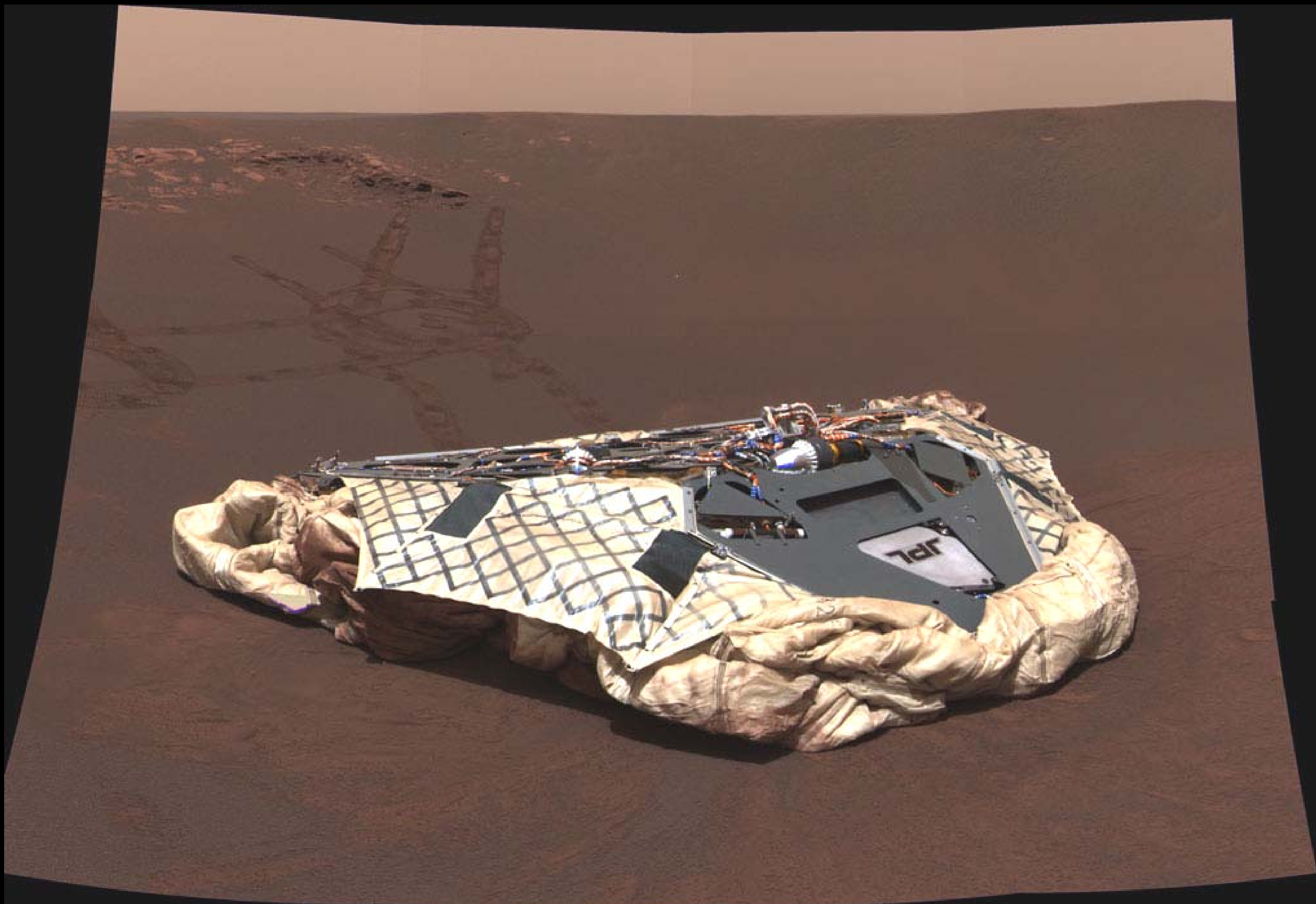


Egress and on with Surface Ops

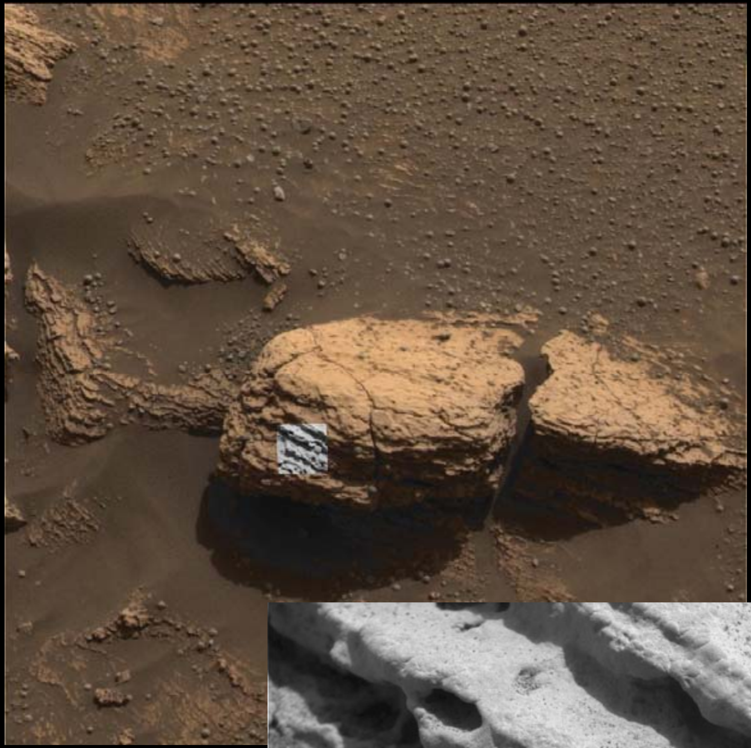


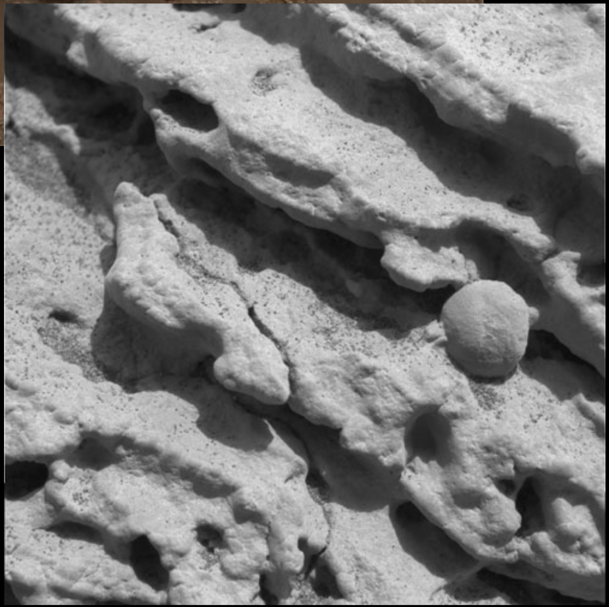


Leaving the Lander Behind

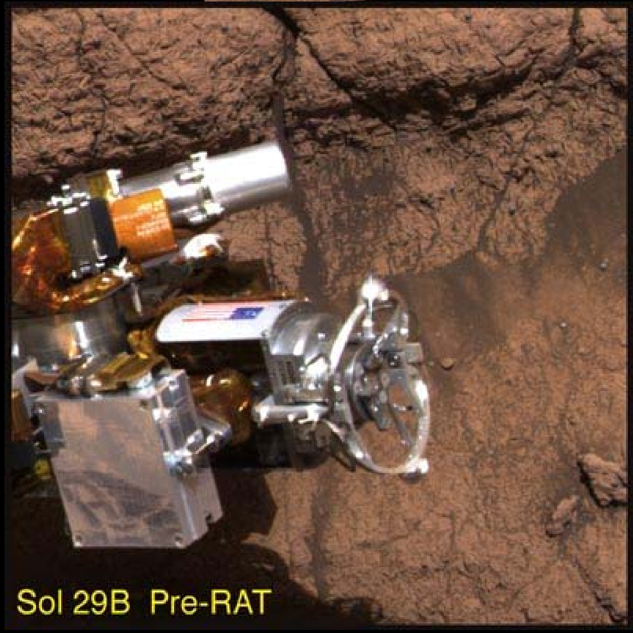


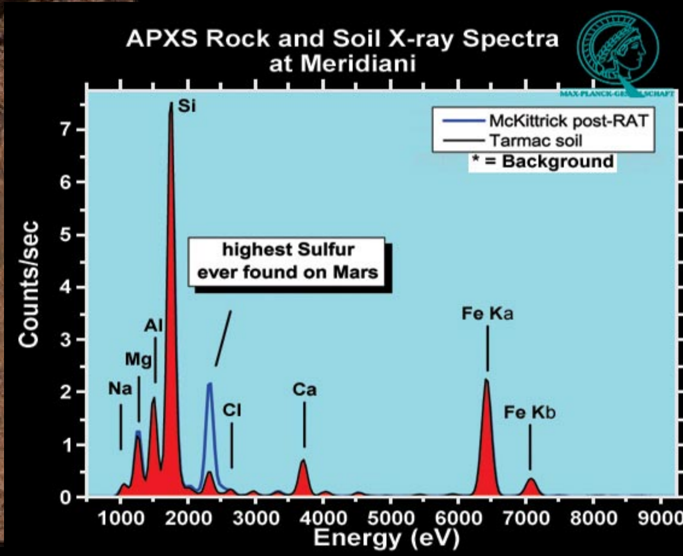
Investigating Stone Mountain



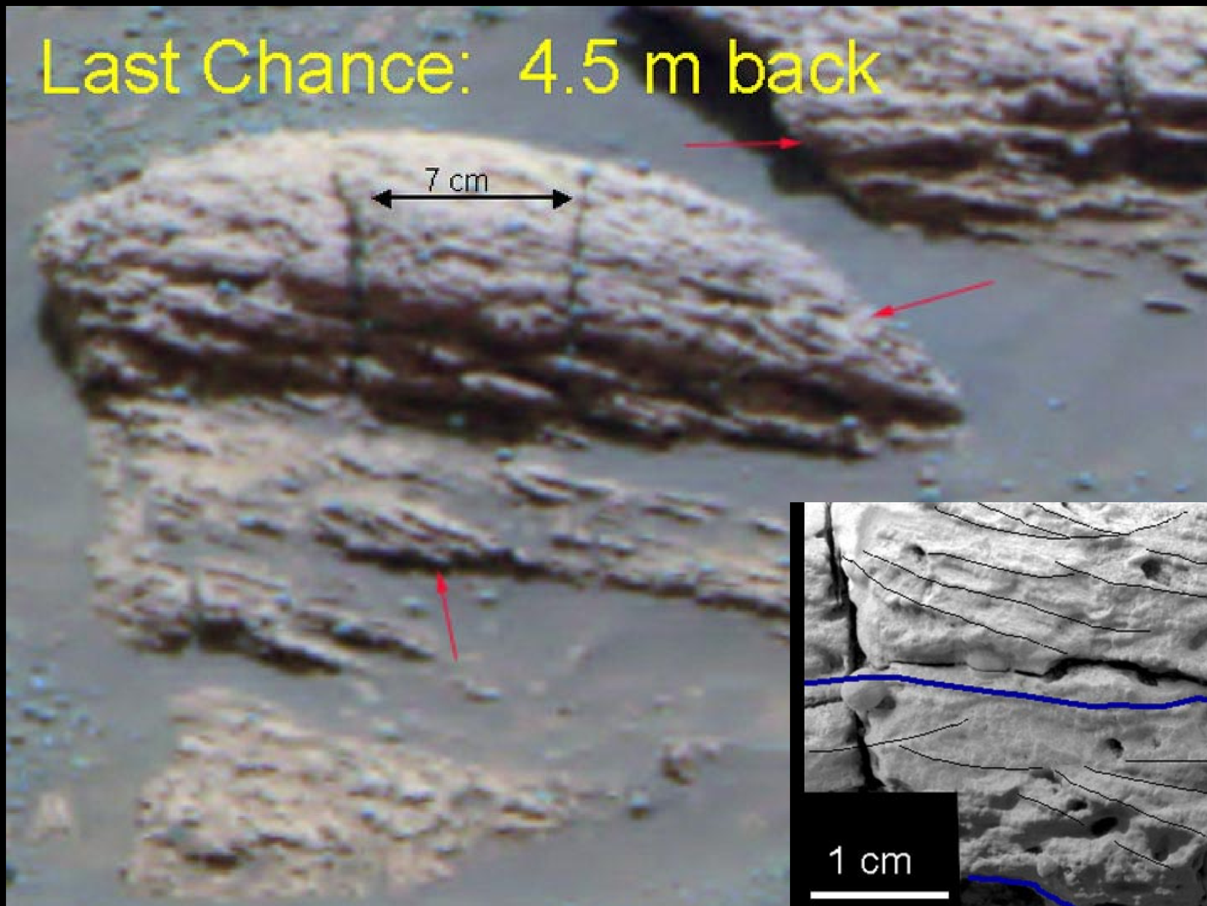


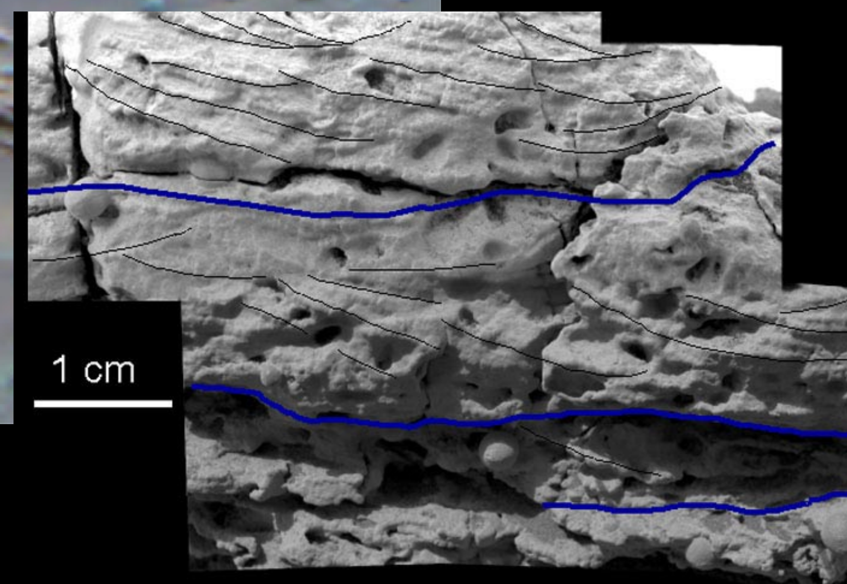
Grinding into El Capitan





Searching for Signs of Water

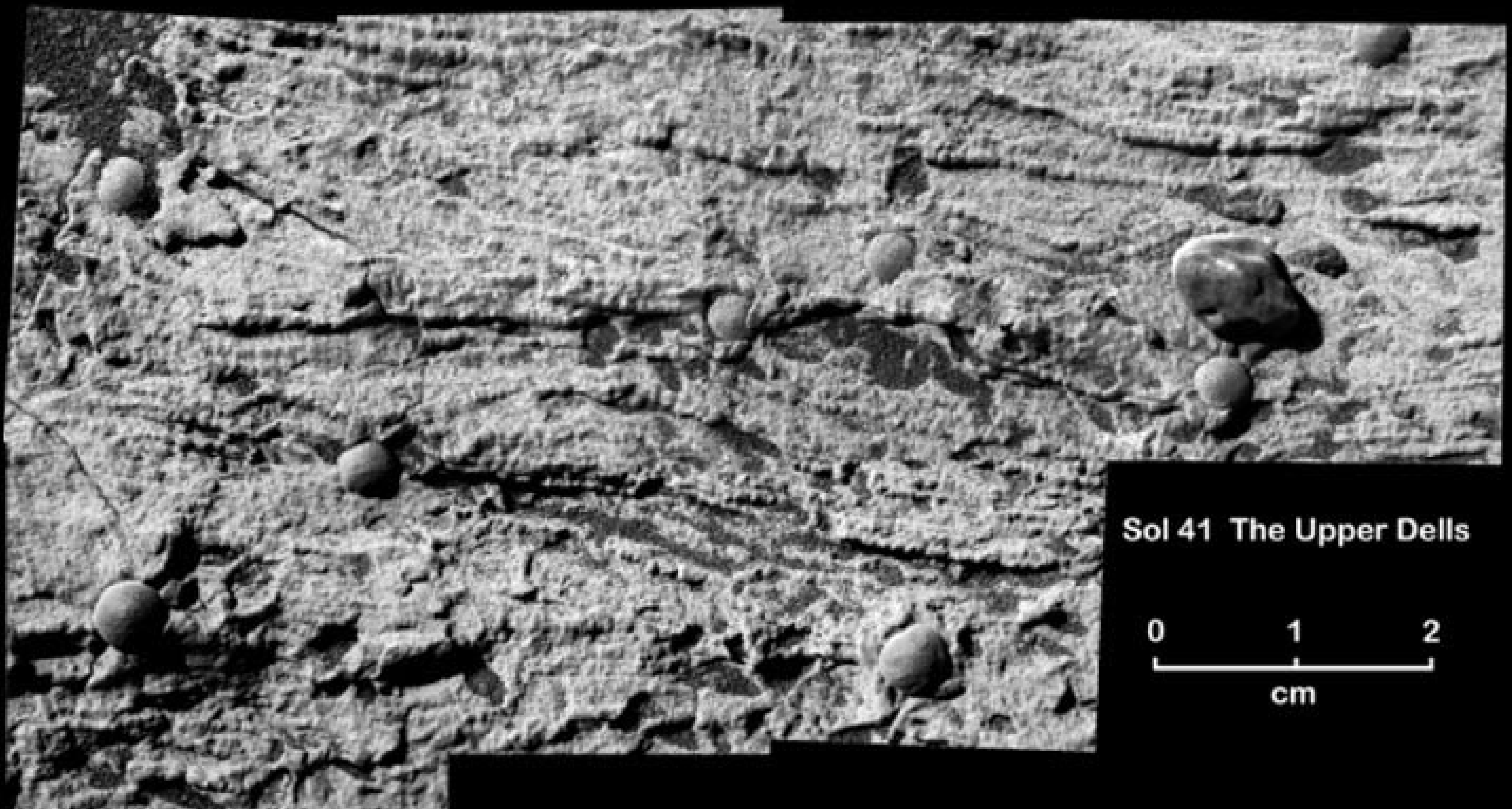




Last Chance MI Mosaic

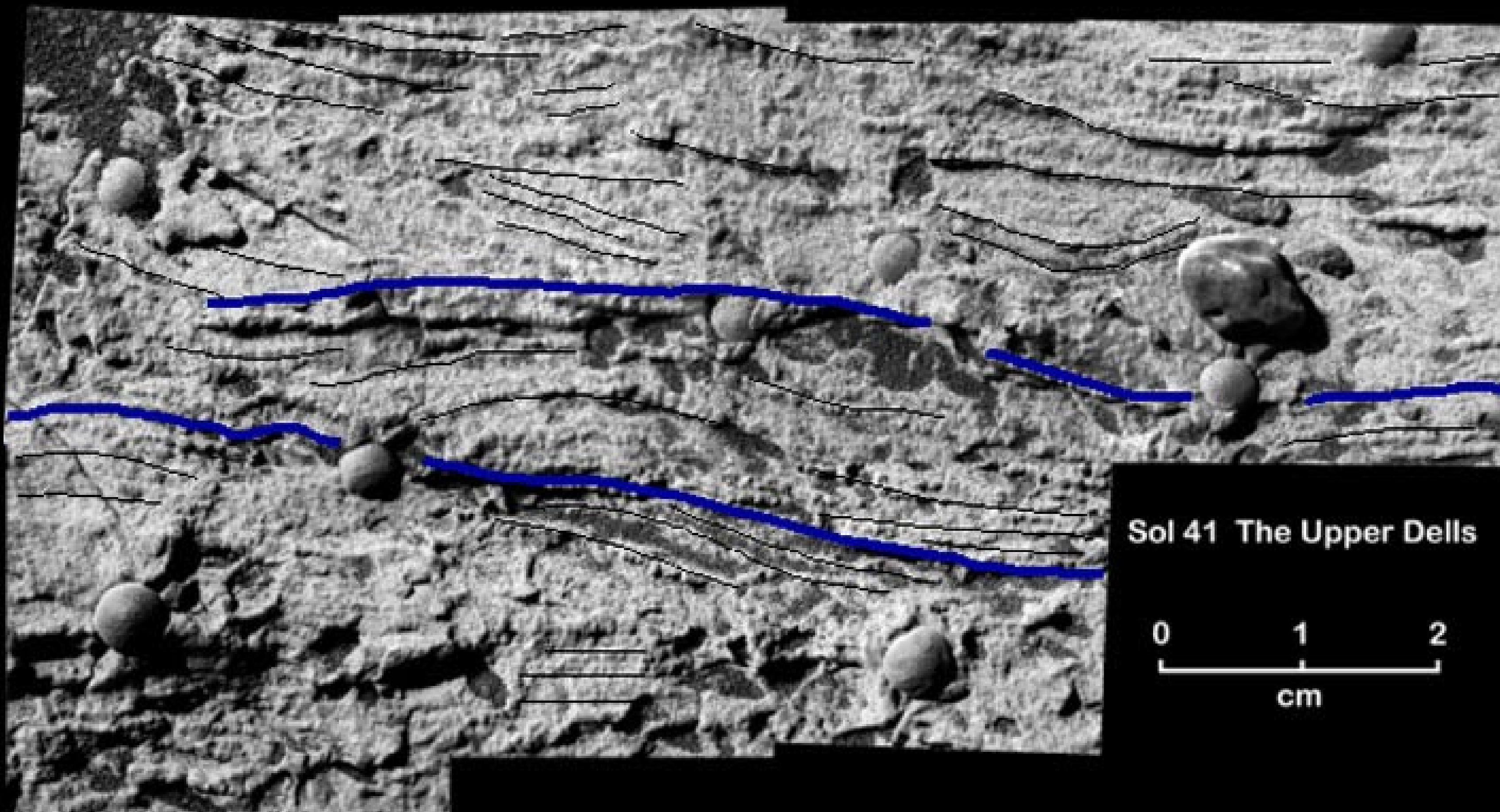
Searching for Signs of Water

Upper Dells MI Mosaic

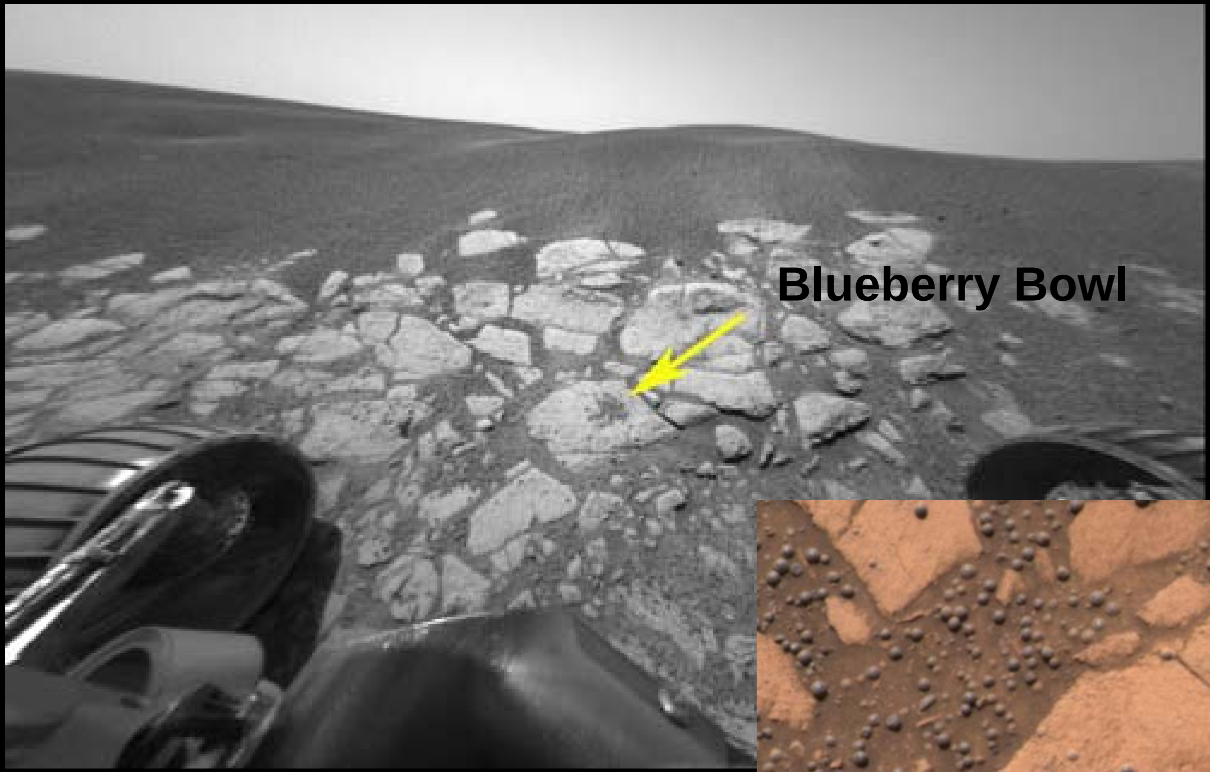


Searching for Signs of Water

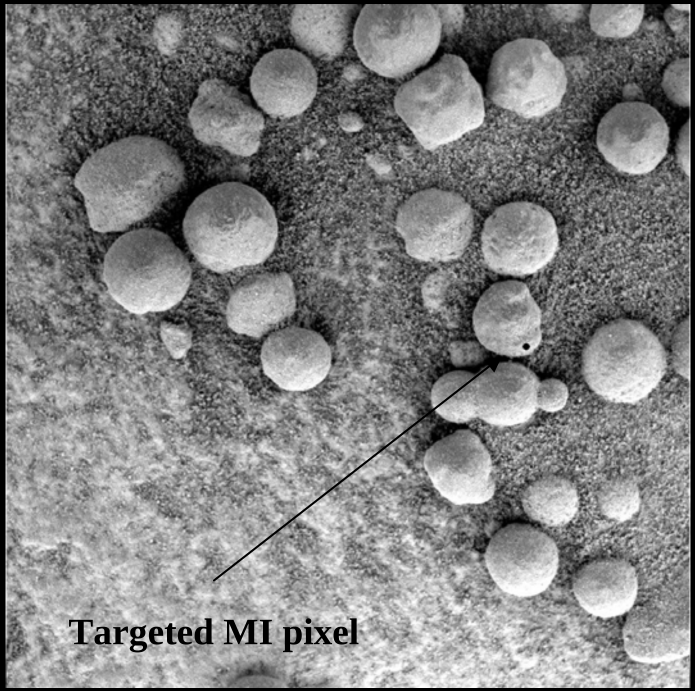
Upper Dells MI Mosaic

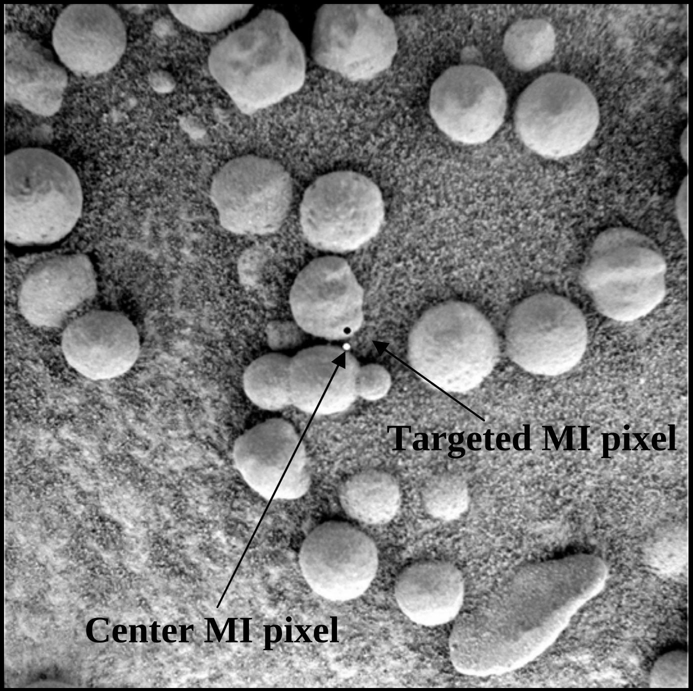


Foraging for Blueberries



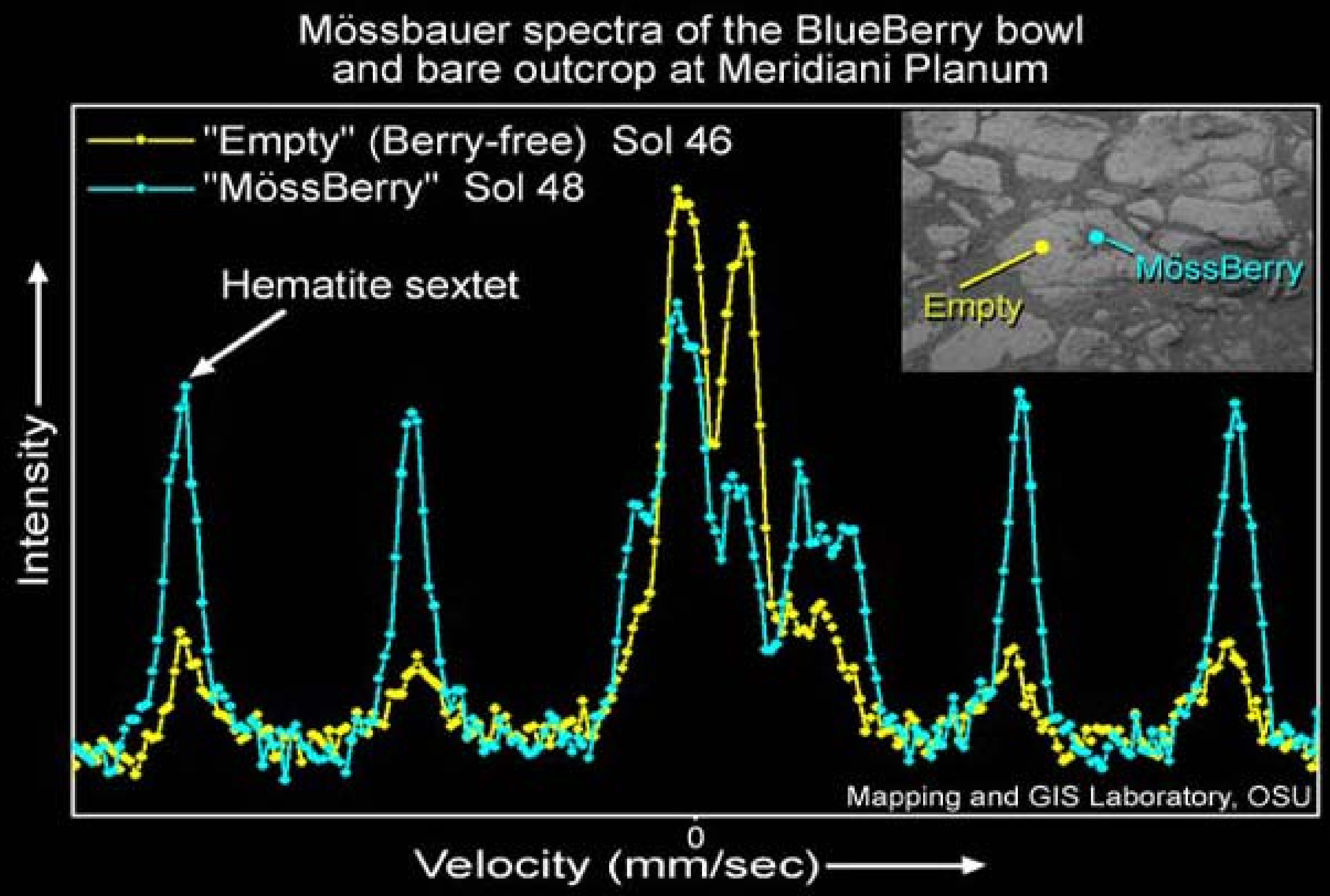
Foraging for Blueberries





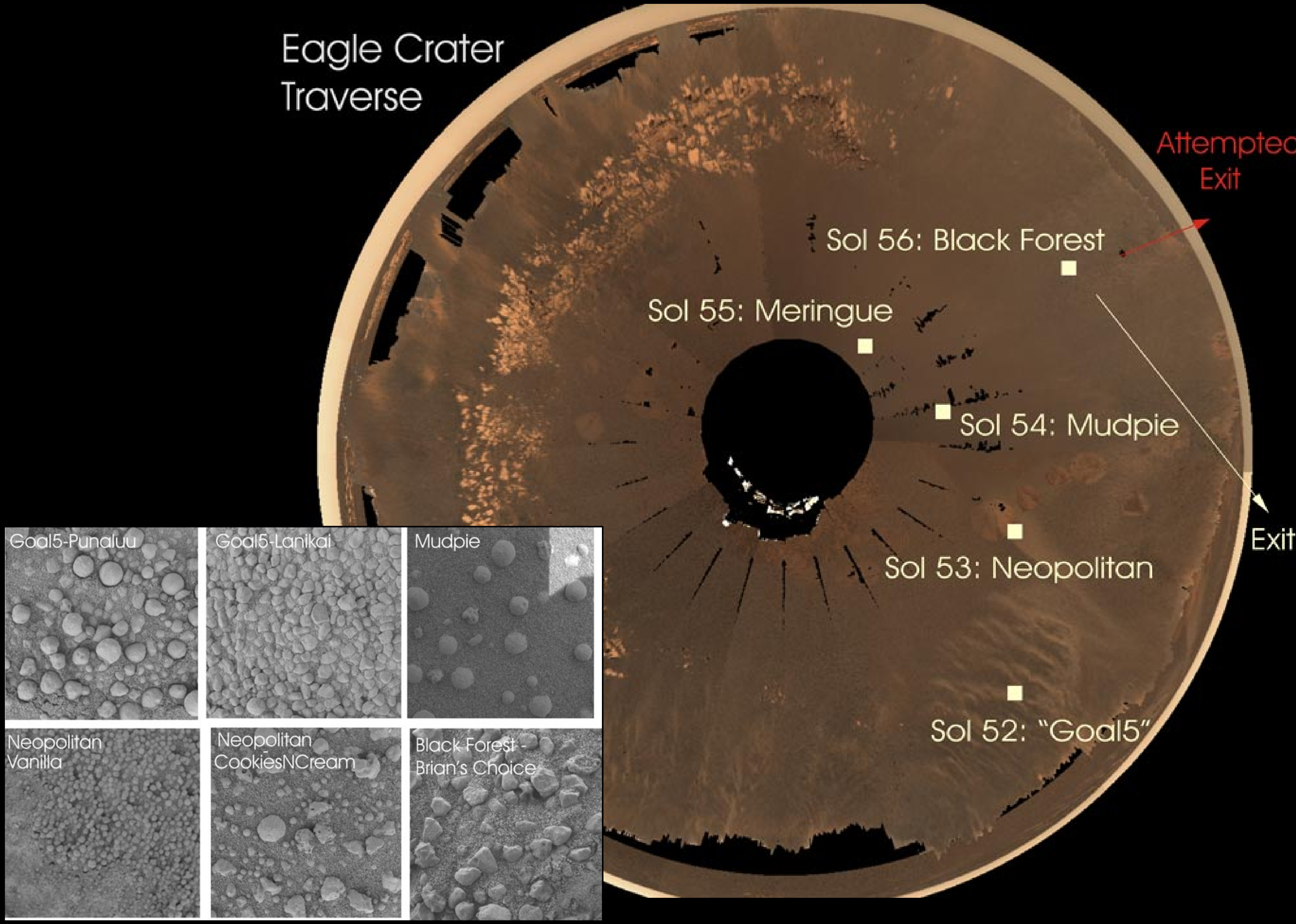
- Eye-in-hand technique used to target specific blueberry cluster for targeting MB placement from MI image
- The targeted pixel is approximately 26 pixels from the center pixel in the MI image which corresponds to a targeting error of 0.8 mm (all from 200 million miles away)

Foraging for Blueberries



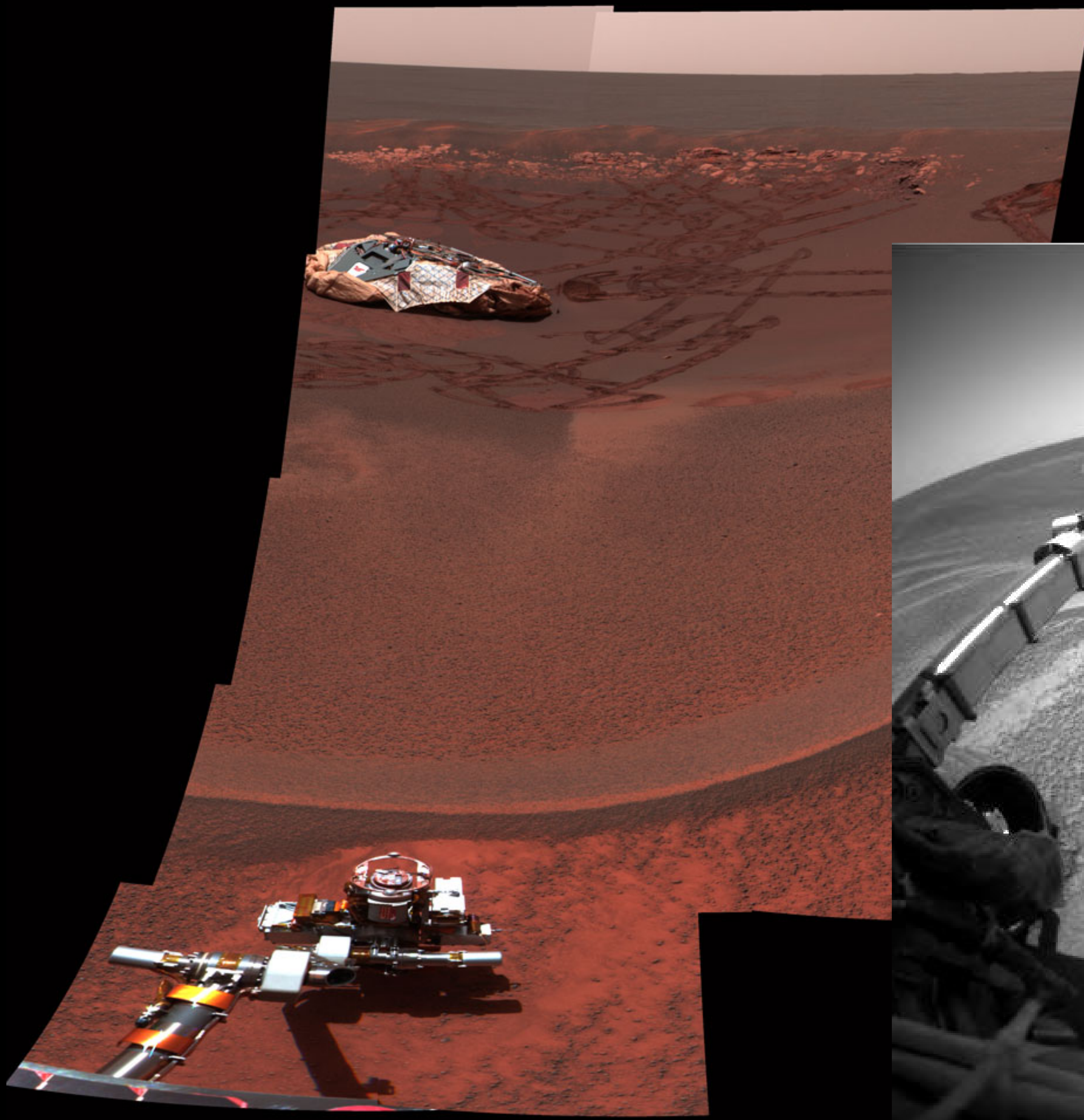
- MB spectrum shows giant hematite lines on berry cluster

Moving On

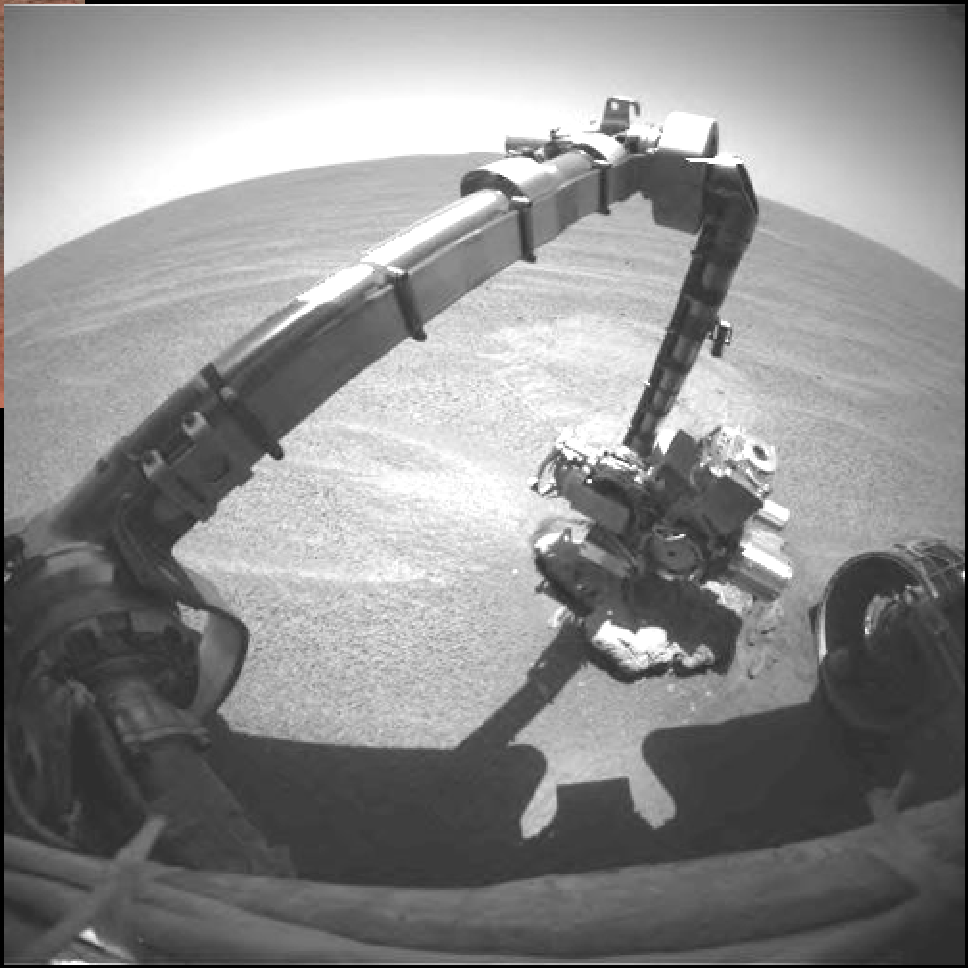


Eagle Crater
Traverse
Attempted
Exit
Sol 56: Black Forest
Sol 55: Meringue
Sol 54: Mudpie
Exit
Sol 53: Neopolitan
Sol 52: "Goal5"
Goal5-Punaluu
Goal5-Lanikai
Mudpie
Neopolitan
Vanilla
Neopolitan
CookiesNCream
Black Forest -
Brian's Choice

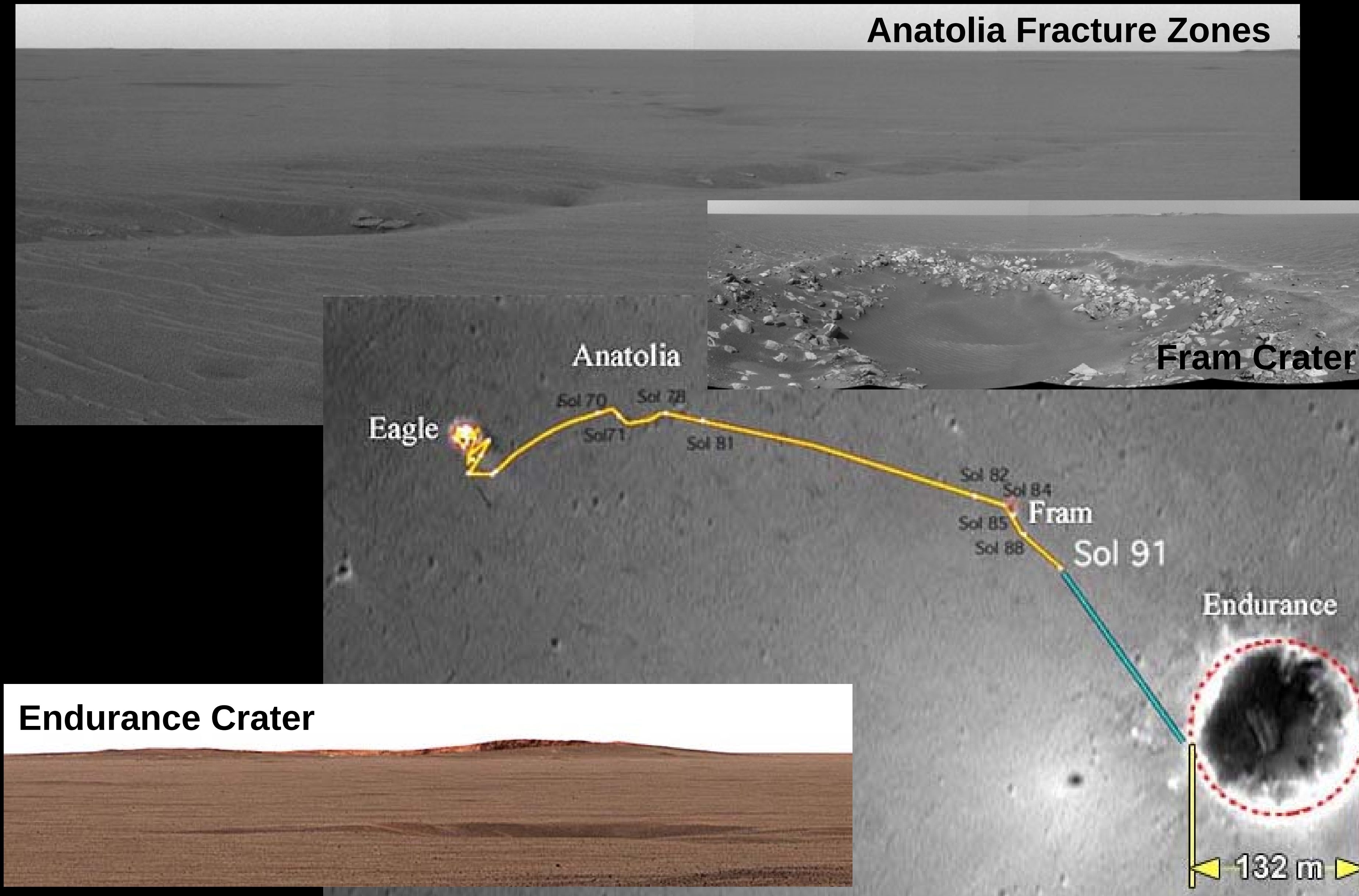
Leaving Eagle Crater



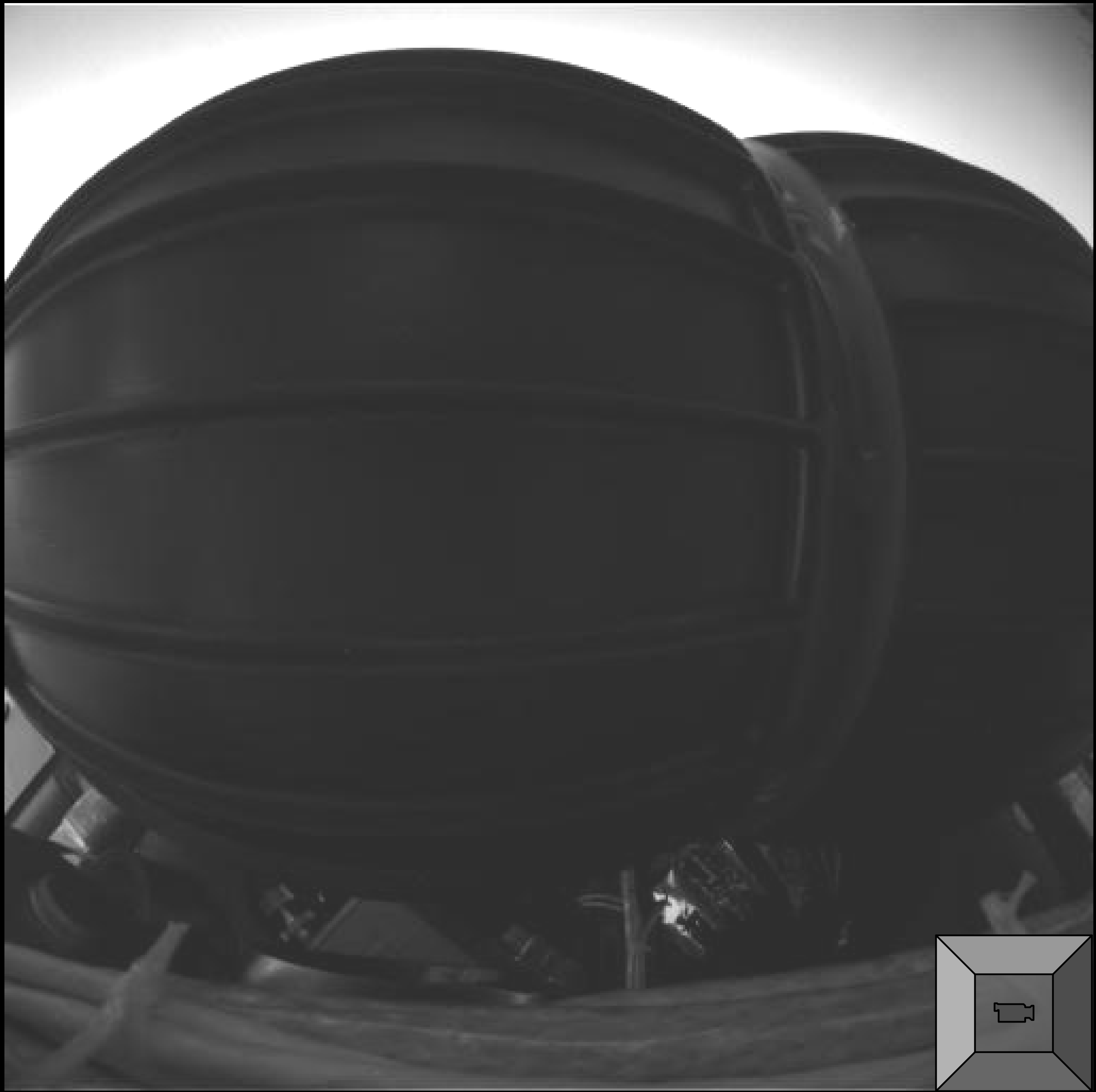
Investigating Bounce Rock



From here to Endurance Crater



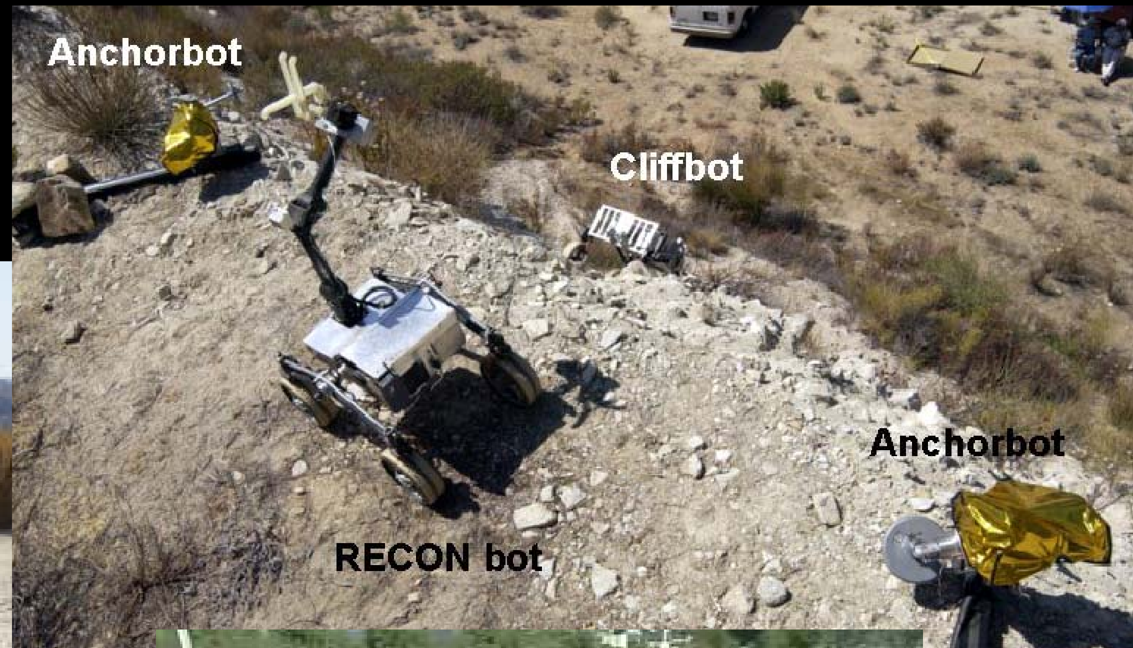
90 Sols on Mars!



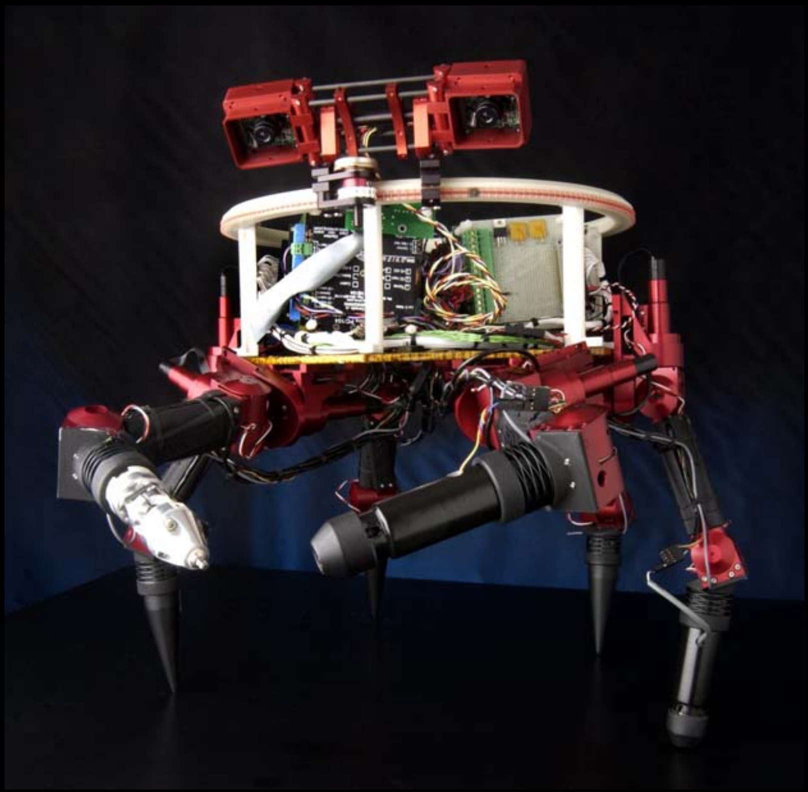
The Future

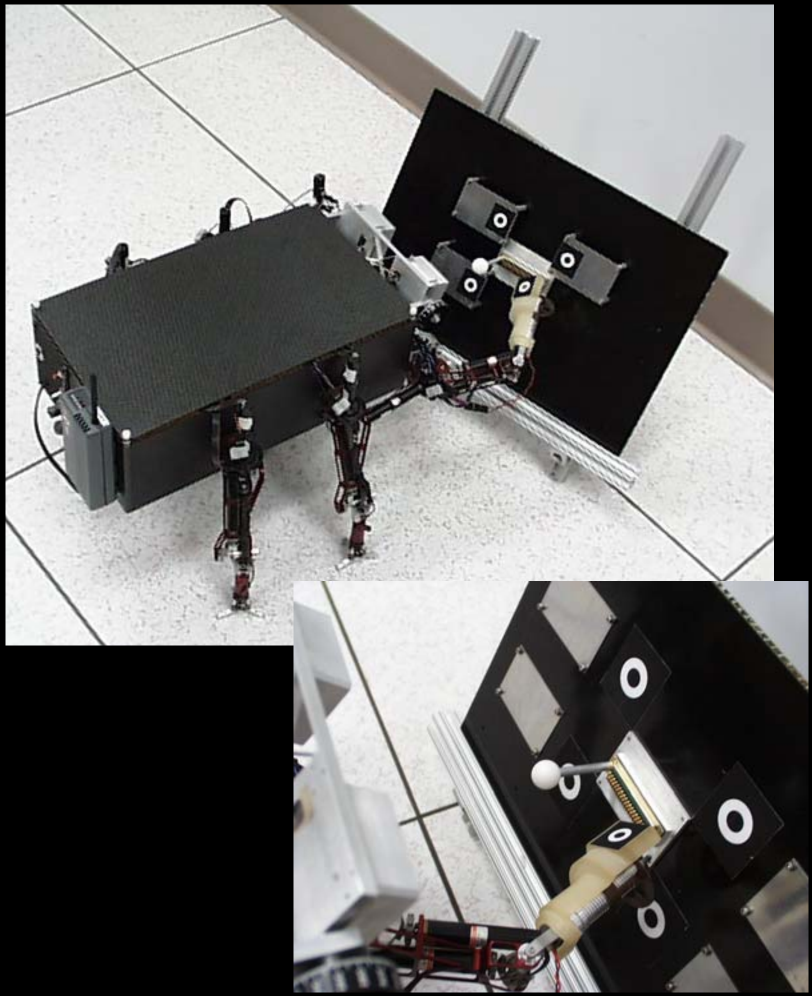
Rough Terrain Access

Multi-Agent Systems

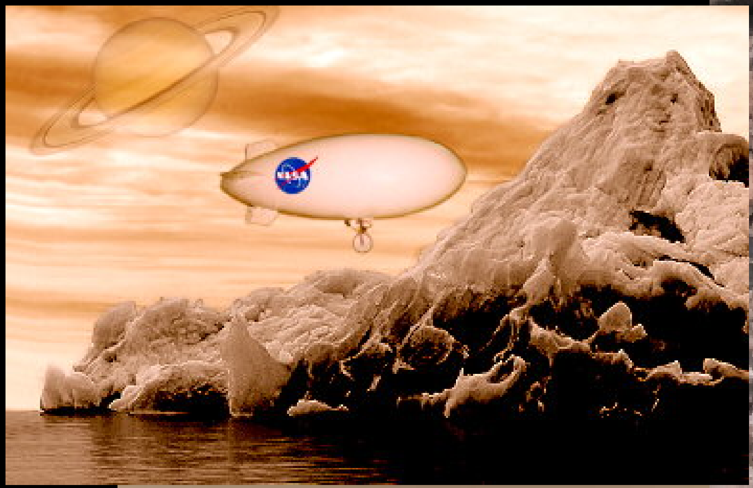


Robotic Construction





Aerial and Subsurface Exploration



Join the Adventure!

http//marsrovers.jpl.nasa.gov