This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Broader Interests and Applications
The view of a JPL Hardware Engineer

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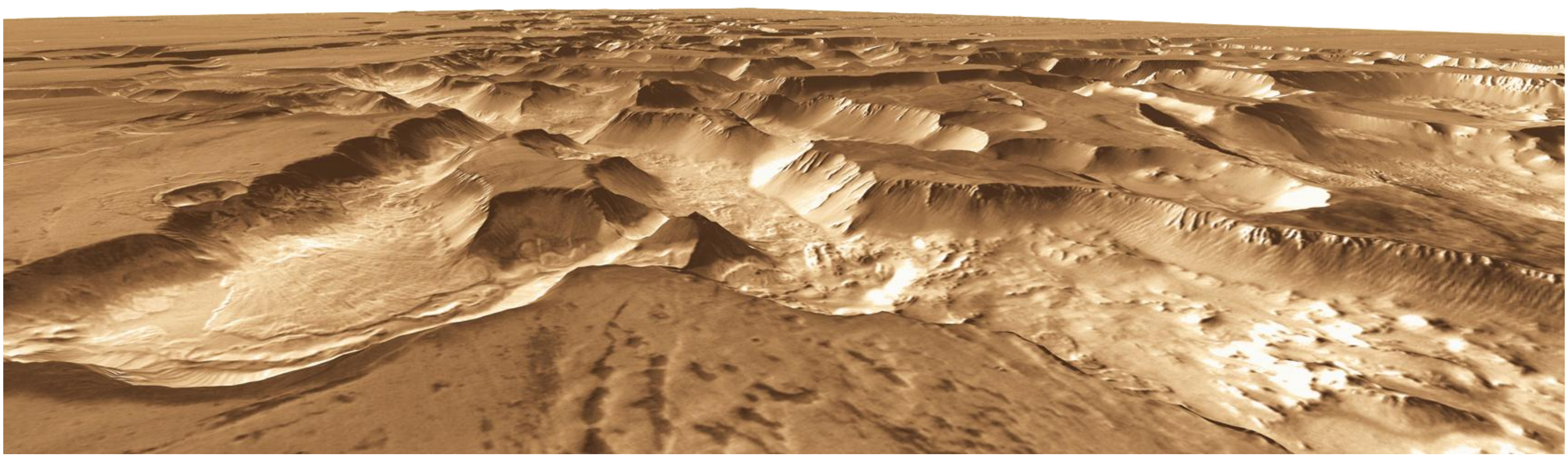
August 19, 2011



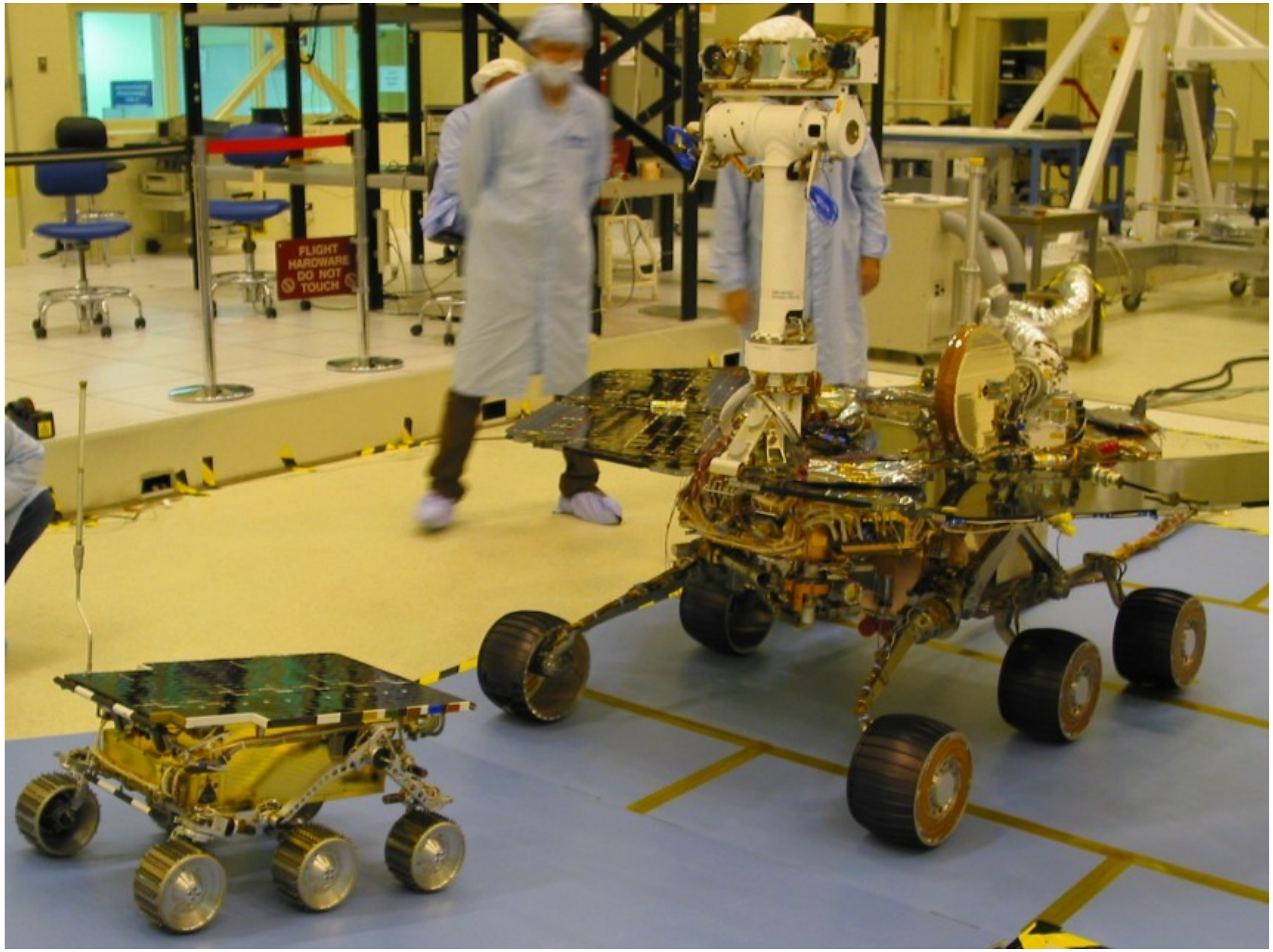
MER Flight Vehicle, 'Spirit', during Integration & Test

MER Mobility Design

- The Rocker-Bogie mobility suspension is comprised of 6 driven wheels, with the outer 4 wheels steerable

- The Rocker-Bogie suspension utilizes a differential and linkages to effectively equilibrate the wheel loads during drives

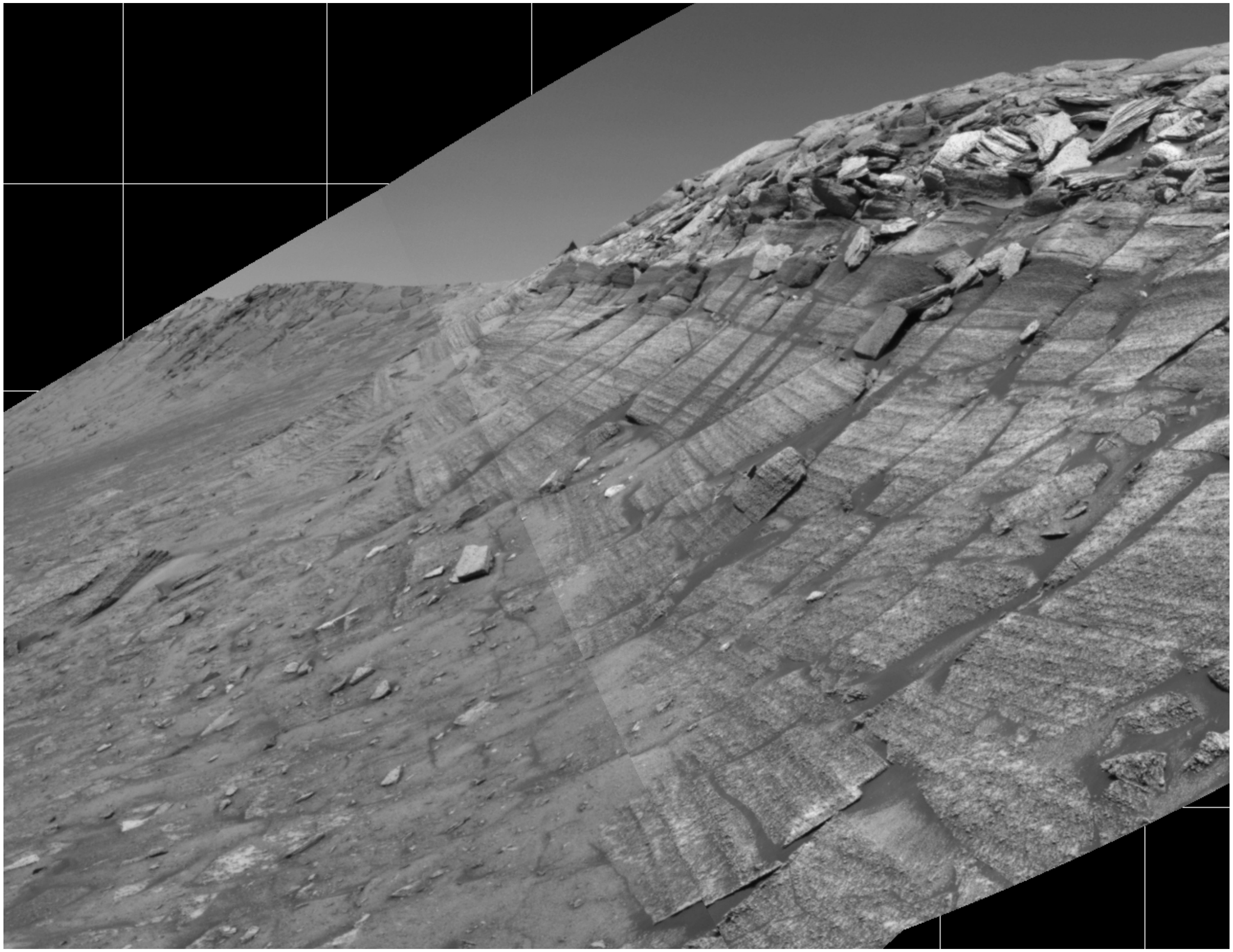
- The first rover to Mars, Sojourner, also utilized a rocker bogie suspension



The rover *Spirit* shown behind *Marie Curie* from the Mars Pathfinder mission

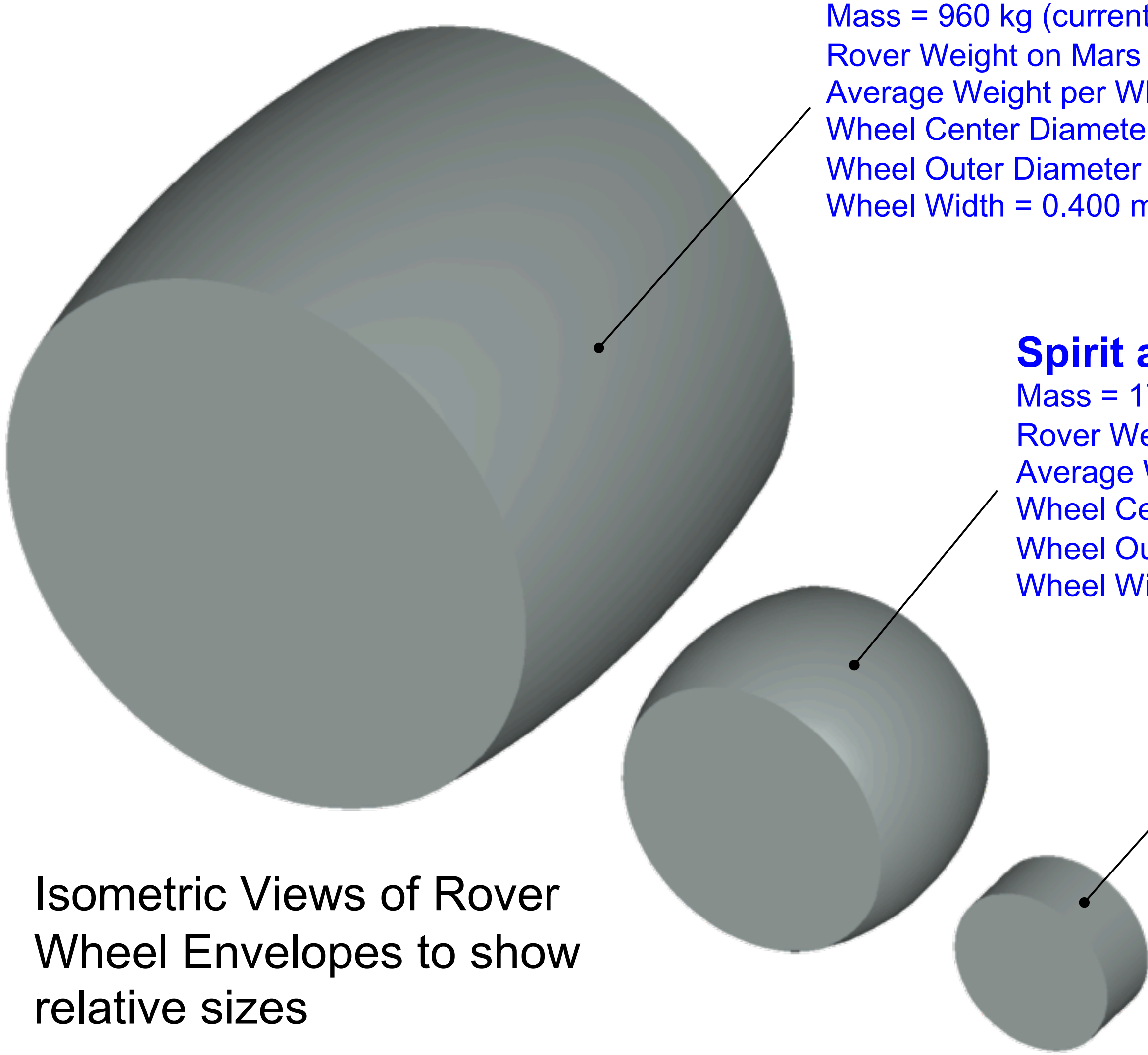
MER Mobility Requirements

- Last 90 “sols” on Mars
- Drive up to 1 km
- Traverse obstacles up to 25 cm in height
- Traverse over very soft soils
- Be statically stable while tilted in any direction up to 45 degrees
- Not be “torque limited”,
- Perform precision drives to science targets
- Wheels designed to achieve a low engineering ground pressure on soft terrain



View from the rover *Opportunity* of the Burns Cliff formation, Endurance crater

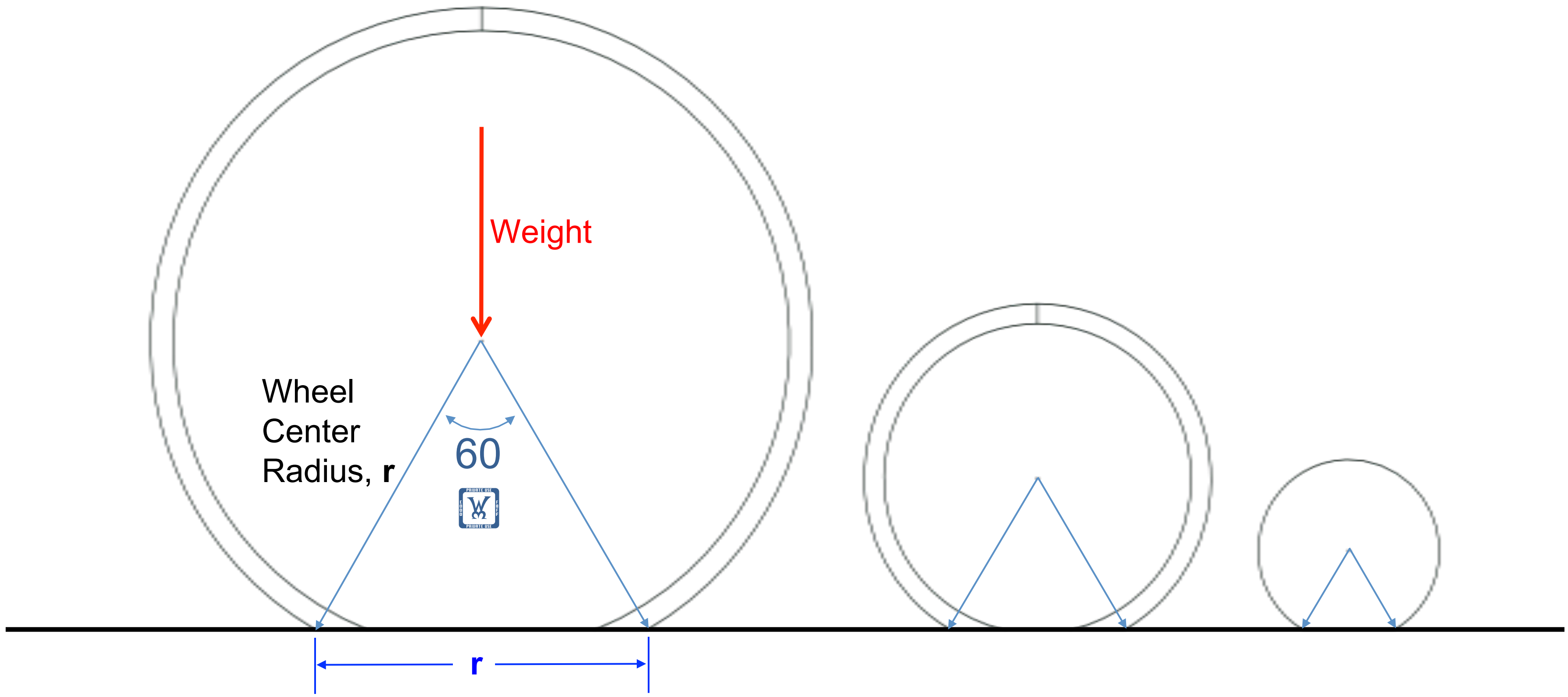
Rover and Wheel Properties



Isometric Views of Rover Wheel Envelopes to show relative sizes

defining Effective Ground Pressure

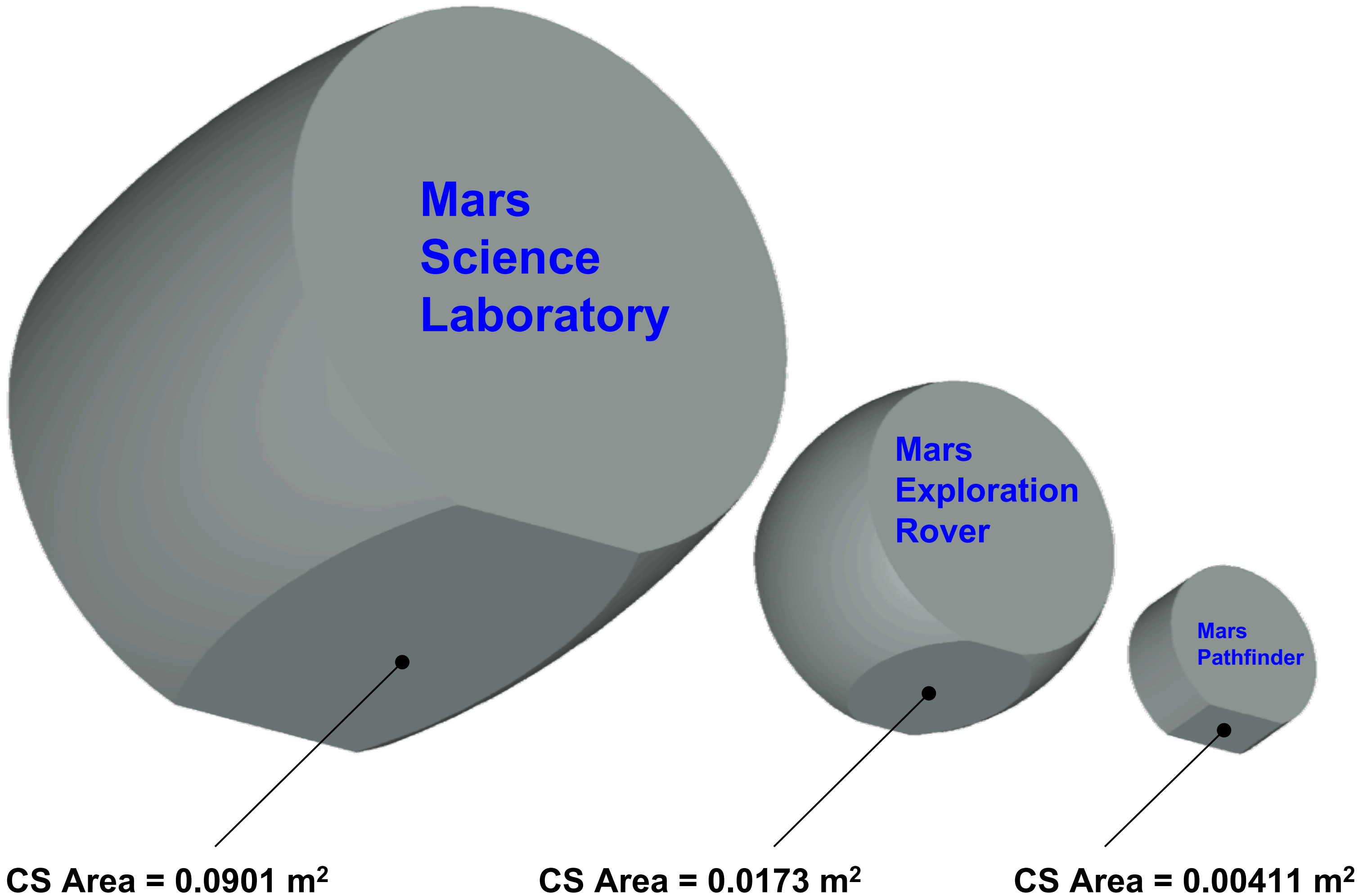
An engineering metric for rover comparisons and scaling



The **Effective Ground Pressure**, EGP, metric is defined as the *average pressure under the average wheel*. The average weight on a wheel is first found by dividing the total vehicle weight on a planetary body by the number of wheels. The EGP is found by dividing the average weight by the cross sectional area of the wheel's contact patch on the ground plane, after the wheel has sunk into a terrain so as to have a contact patch length of one wheel radius. In the case of non-cylindrical tires, the largest radius, usually at the mid-plane is used. When the wheel's periphery has cleats, lugs, or grouser bars; a determination is made as to the amount of their height added to the tire diameter, based on the projected area ratio of these tractive elements.

Cross-Sectional Area of each Wheel's Contact Patch with the Ground Plane:

Determined via CAD Analysis



Effective Ground Pressure Comparisons:

Planetary Rovers on Mars

- Mars Pathfinder – *Sojourner*
  - EGP = Average Weight/CS Area = 6.511 N / 0.00411 m^2 = 1586 N/m^2
    = 1586 Pa **(0.23 psi)**
- Mars Exploration Rover – *Spirit and Opportunity*
  - EGP = Average Weight/CS Area = 109.45 N / 0.0173 m^2 = 6335 N/m^2
    = 6335 Pa **(0.919 psi)**
- Mars Science Laboratory - *Curiosity*
  - EGP = Average Weight/CS Area = 595.3 N / 0.0901 m^2 = 6609 N/m^2
    = 6609 Pa **(0.959 psi)**

MER Mobility Testing

- Testing under mobility conditions was performed on a 5 meter square tilt-able platform called the Variable Terrain Tilt Platform (VTTP)
- The slope of the VTTP could be set between 0 and 30 degrees
- The surface was initially bare, and later covered with dry and loose quartz sand
- Obstacles could also be attached to the platform

Dynamic Test Model rover driving up a 15 deg slope, climbing a 25 cm obstacle

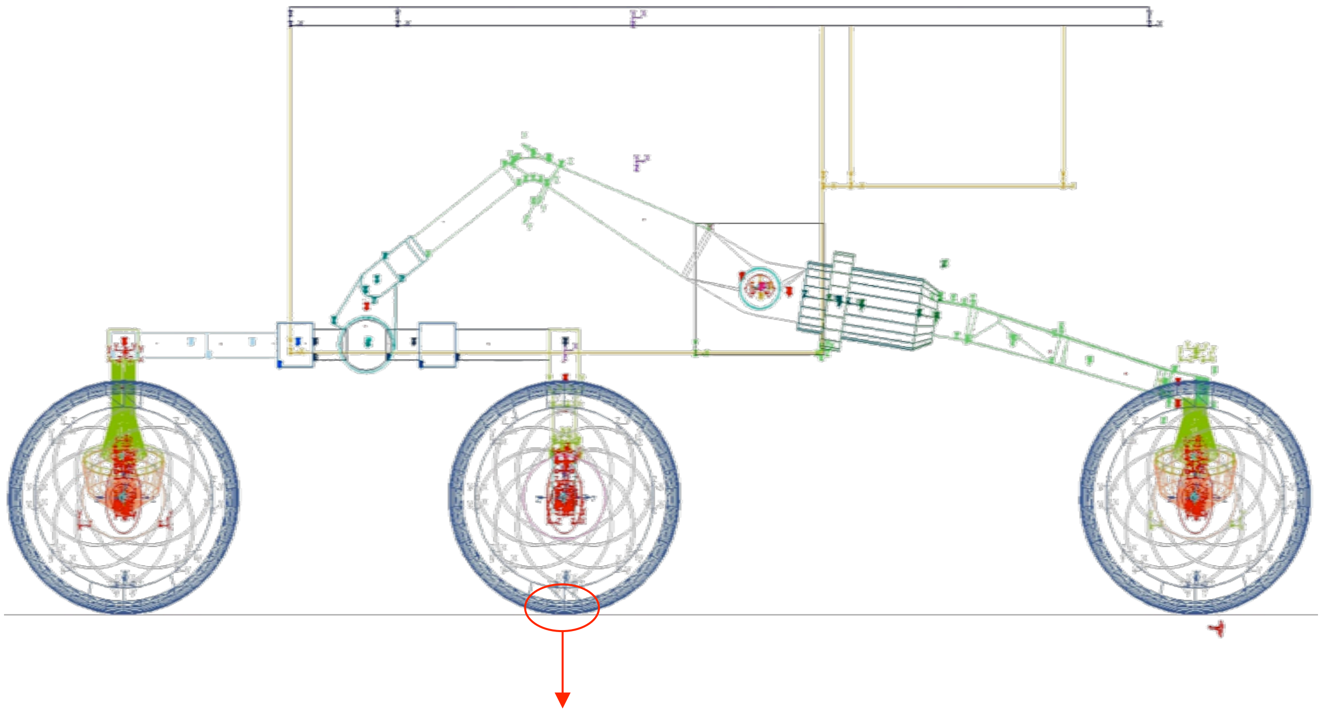
MER Mobility Testing
continued

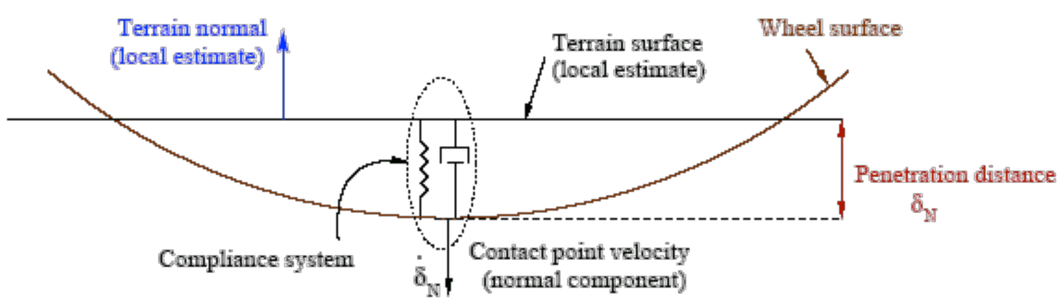
DTM Rover driving cross-slope on the VTTP, at a 20 deg slope, and covered with 20 cm of dry, loose quartz sand

Mobility Dynamic Model

Original Contact Formulation

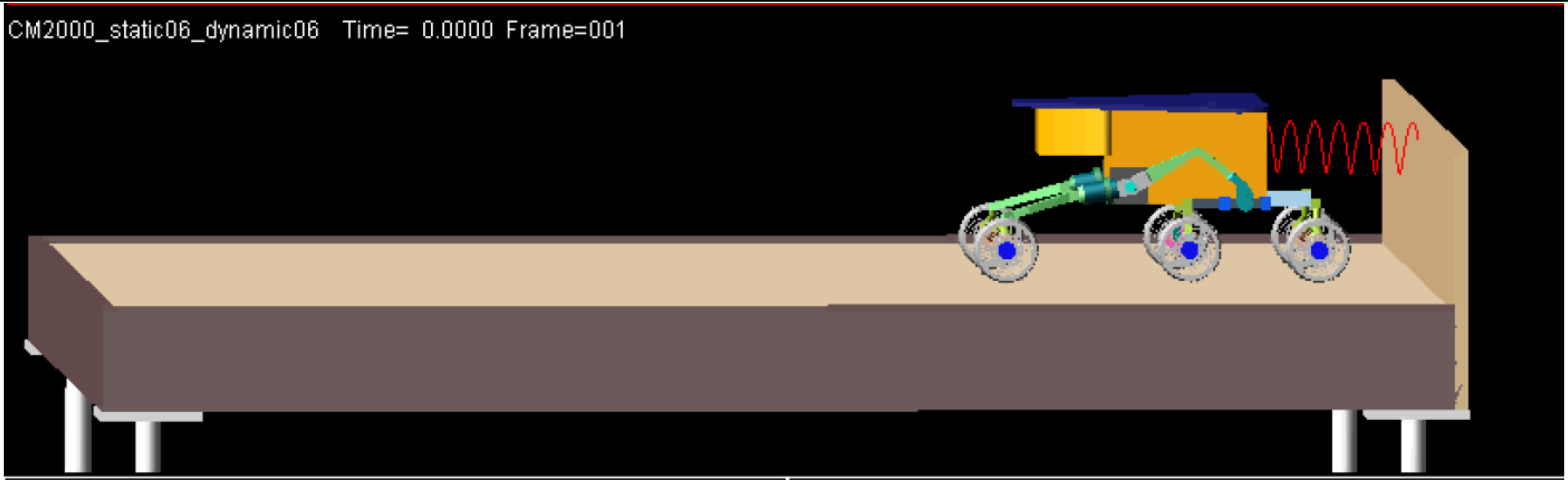
- Physical Idealizations in the **MSC.ADAMS** Rover Model
  - Rigid WEB with mass and inertia
  - Mass and stiffness based on FEM
  - Compliance in suspension, wheels, and torque tube
  - All struts and tubes modeled with Timoshenko beam forces
  - Differential relationship added algebraically
  - Empirical values for damping and friction

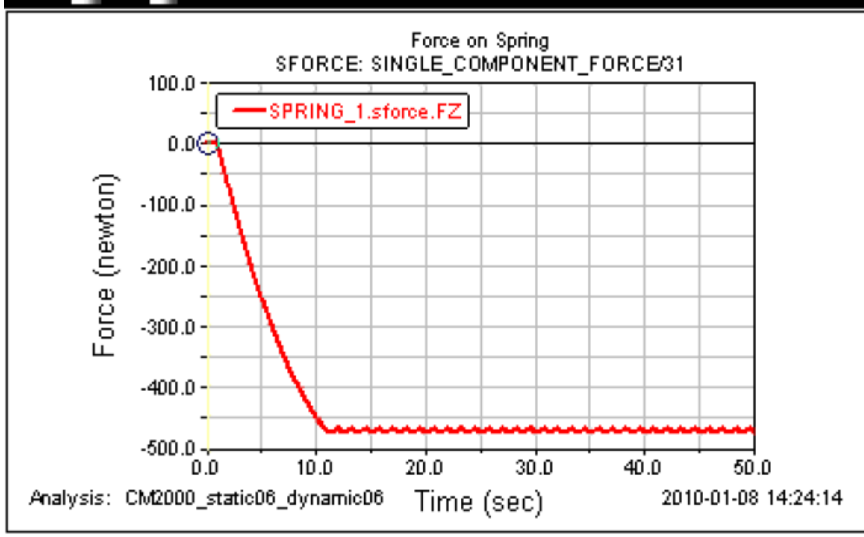


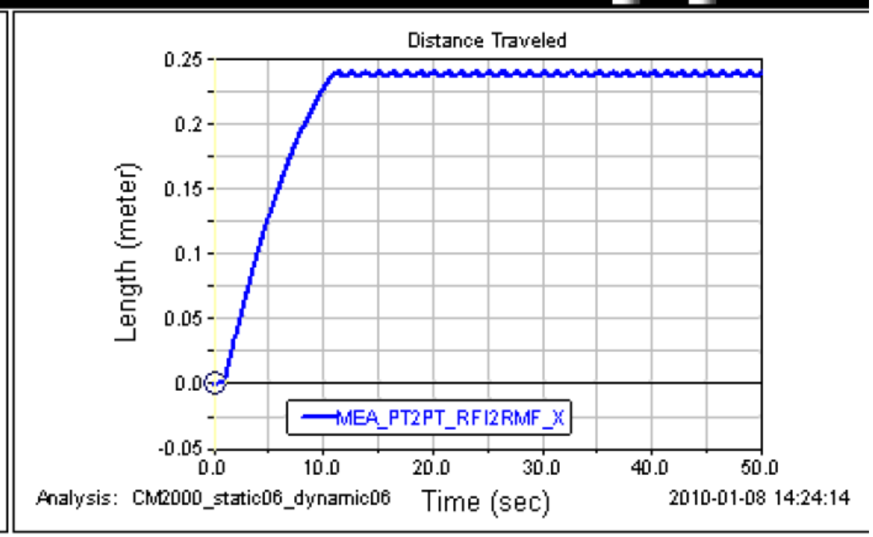


Preliminary ADAMS Simulations

Current development focuses on Terramechanics



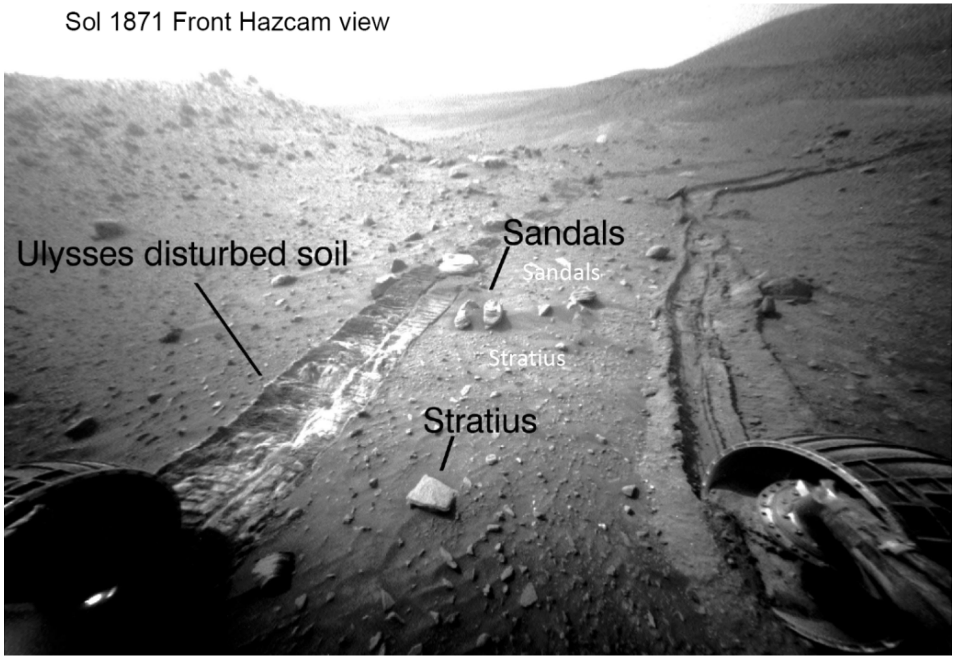




As a result of Spirits mobility issues, a team led by the Project's Deputy Principal Investigator, Prof. Ray Arvidson of Washington University in St. Louis, has begun employing Multi-Body Dynamic Simulations, utilizing the commercial software MSC.ADAMS, to analyze the wheel terrain interaction, or Terramechanics of Spirit in the hopes of freeing her

Spirit's Predicament

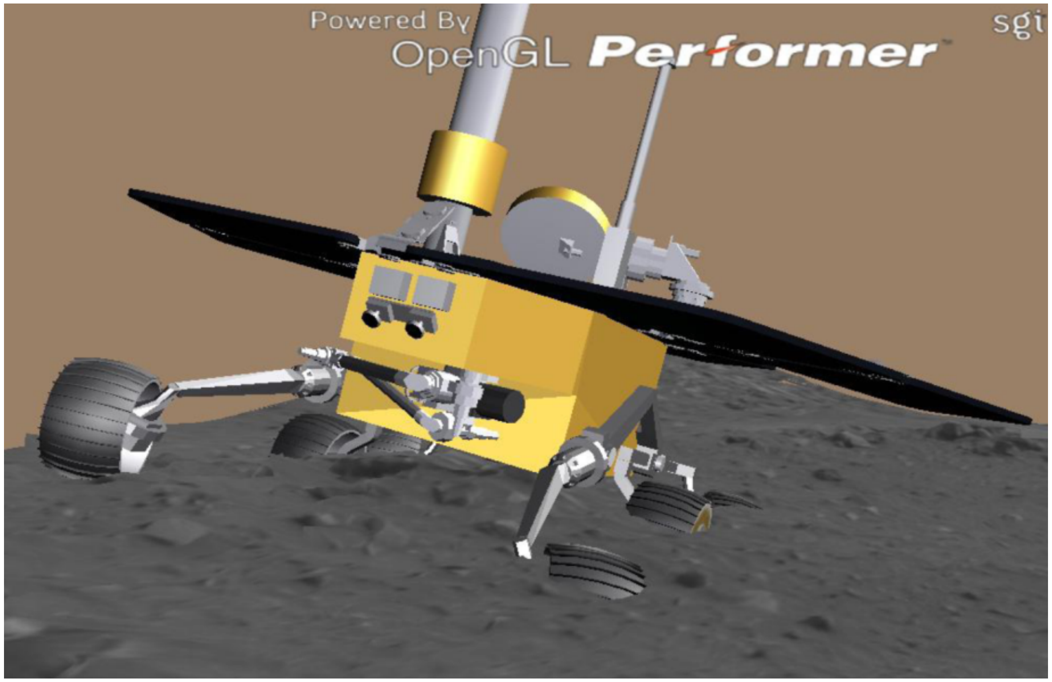
Since Sol 1871



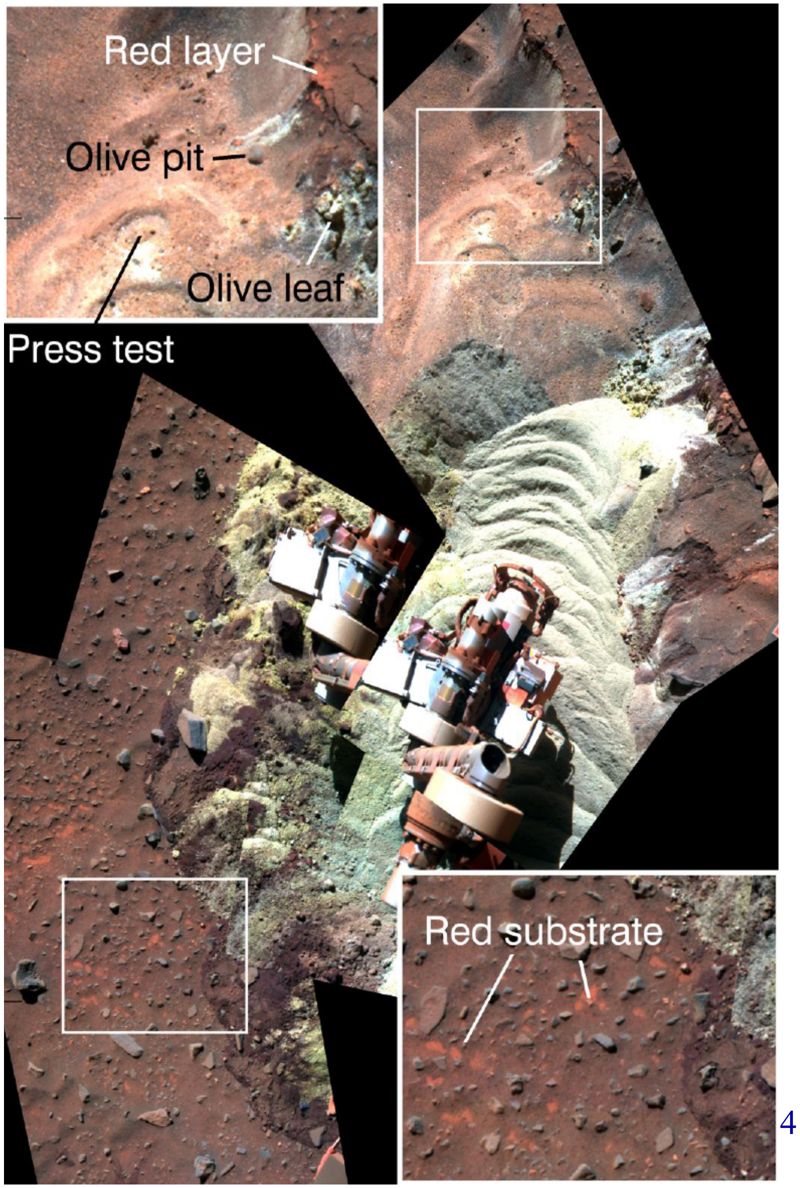
View from the Front Hazard Avoidance Camera on Sol 1871. Note that Spirit has been driving in reverse, dragging its right-front wheel behind it. The right-front wheel has been un-drivable since ~ Sol 1000.

View from the Rear Hazard Avoidance Camera on Sol 1871. This image shows the reverse driving direction of Spirit with the right-rear wheel nearly fully embedded, and with the left-rear wheel buried up to the radius of the wheel.

Details of Spirit's Embedding



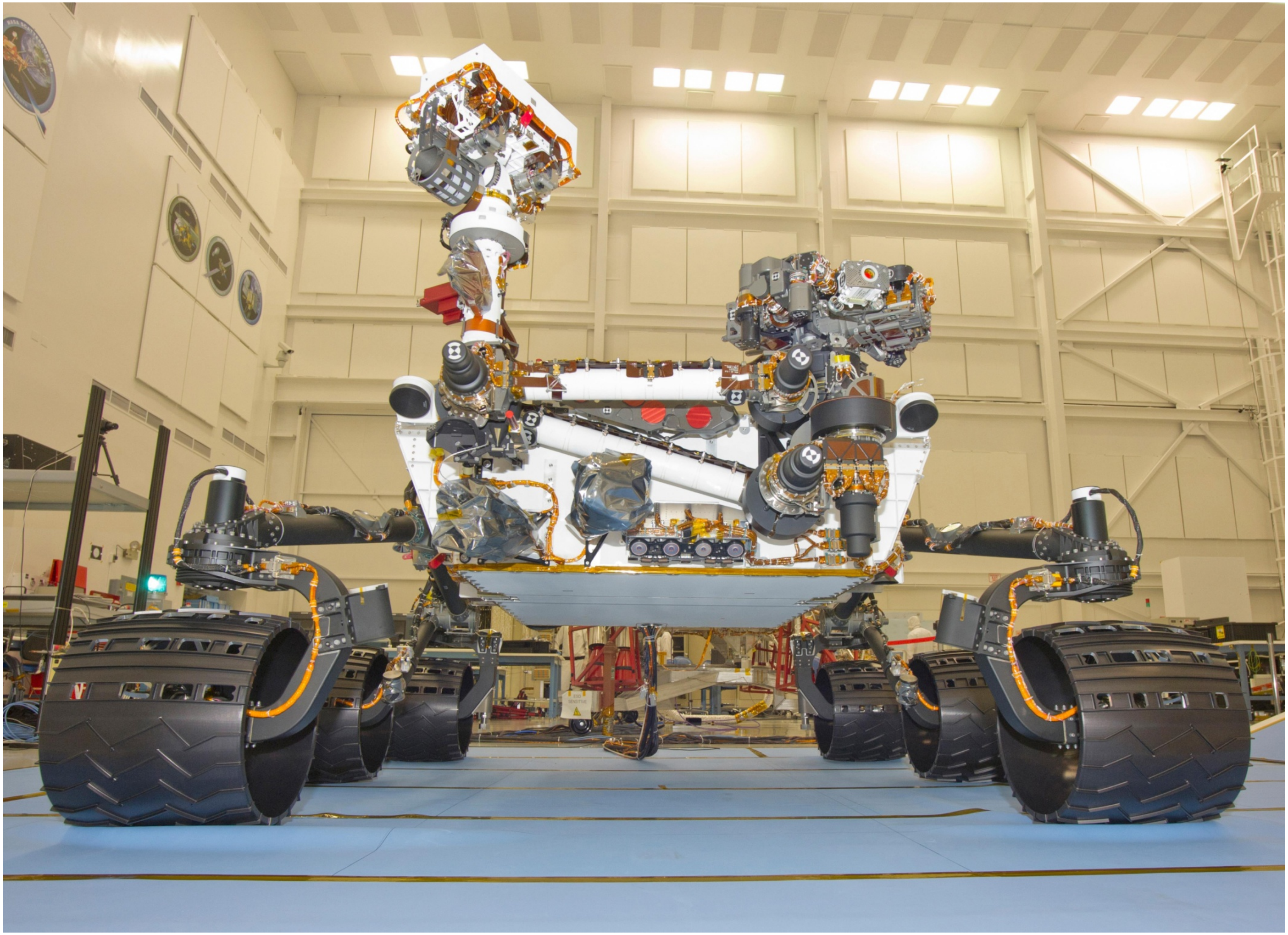
Ground support software visualization of Spirit's embedding



Rover color images, generated on the ground, from the Panoramic Cameras, showing the deployment of the robotic arm and the science instruments to the disturbed soft soils that having caused Spirit's embedding

MER SSTB (Surface System Test-Bed) Rover being driven into an embedding situation in a *Simulant* composed of Diatomaceous Earth and Fine Clay, to test extrication strategies for the Spirit rover

MSL Flight Rover, Curiosity, Front View



MSL Engineering Model being Tested on Dry, Loose Sand on a 20 Degree Slope