Development of the Mars Exploration Rover Mobility System

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Premium Partners:

Mission Overview - Description

- The Mars Exploration Rover, MER, Project started in May 2000
- Two Identical rovers, Spirit and Opportunity, launched in June and July of 2003
- Spirit landed on Mars on Jan. 4 of 2004, Opportunity landed 3 weeks later
- Both rovers are still going strong, but definitely showing their age

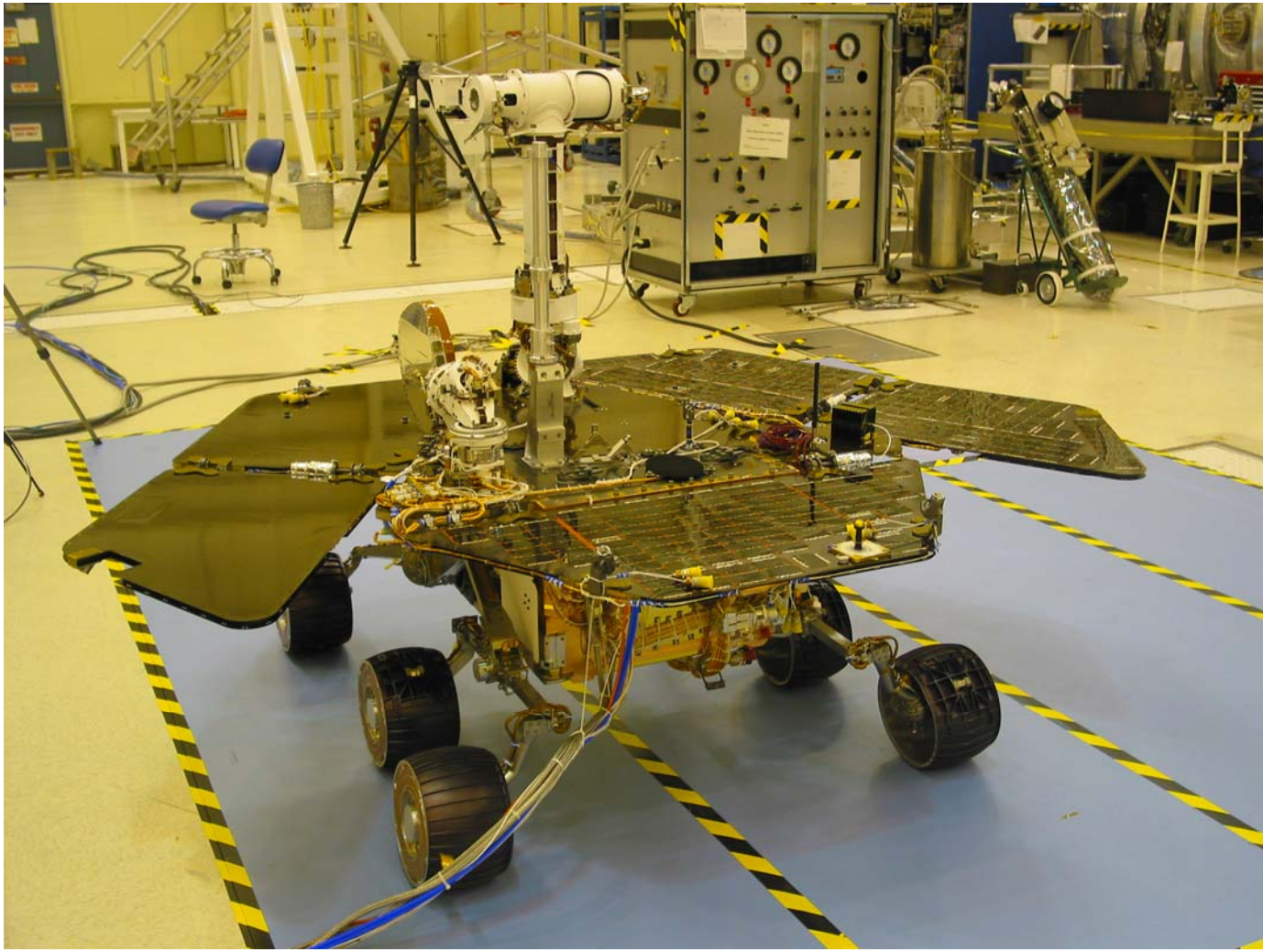


Figure 1. MER Flight Vehicle 'Spirit' during Integration & Test

Mission Overview - Science

- Goal: “Follow the Water”, was Mars ever warm and wet?
- Water along with Energy and Nutrients is required for life
- Spirit was sent to Gusev crater, a dry lake bed
- Opportunity was sent to Meridiani Planum, an area on Mars shown by Orbiters to have large amounts of Hematite

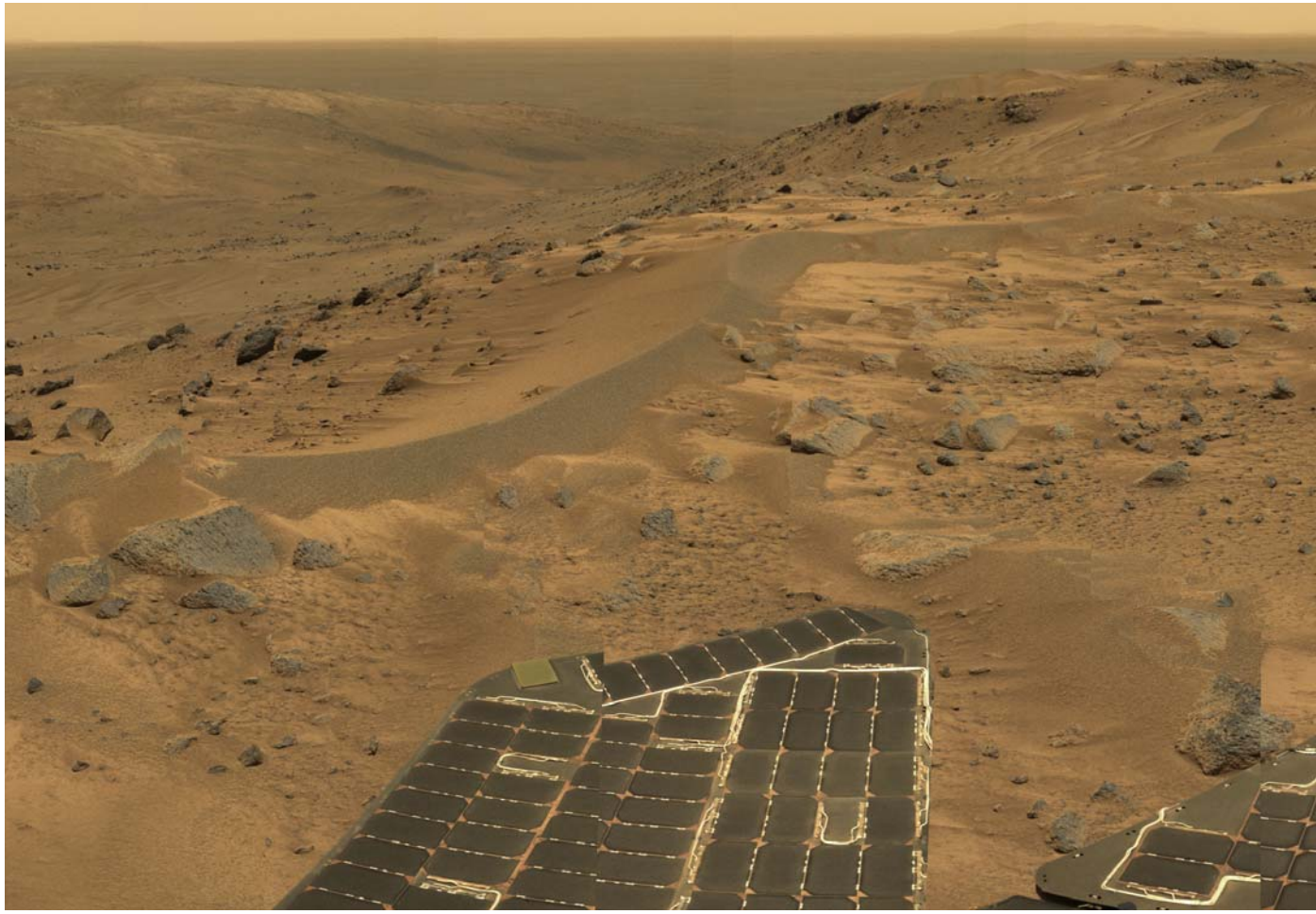


Figure 2. View from Mars, atop the Columbia Hills in Gusev Crater, taken by the rover Spirit

Mission Overview – Mobility Requirements

- The rovers were required to:
  - 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

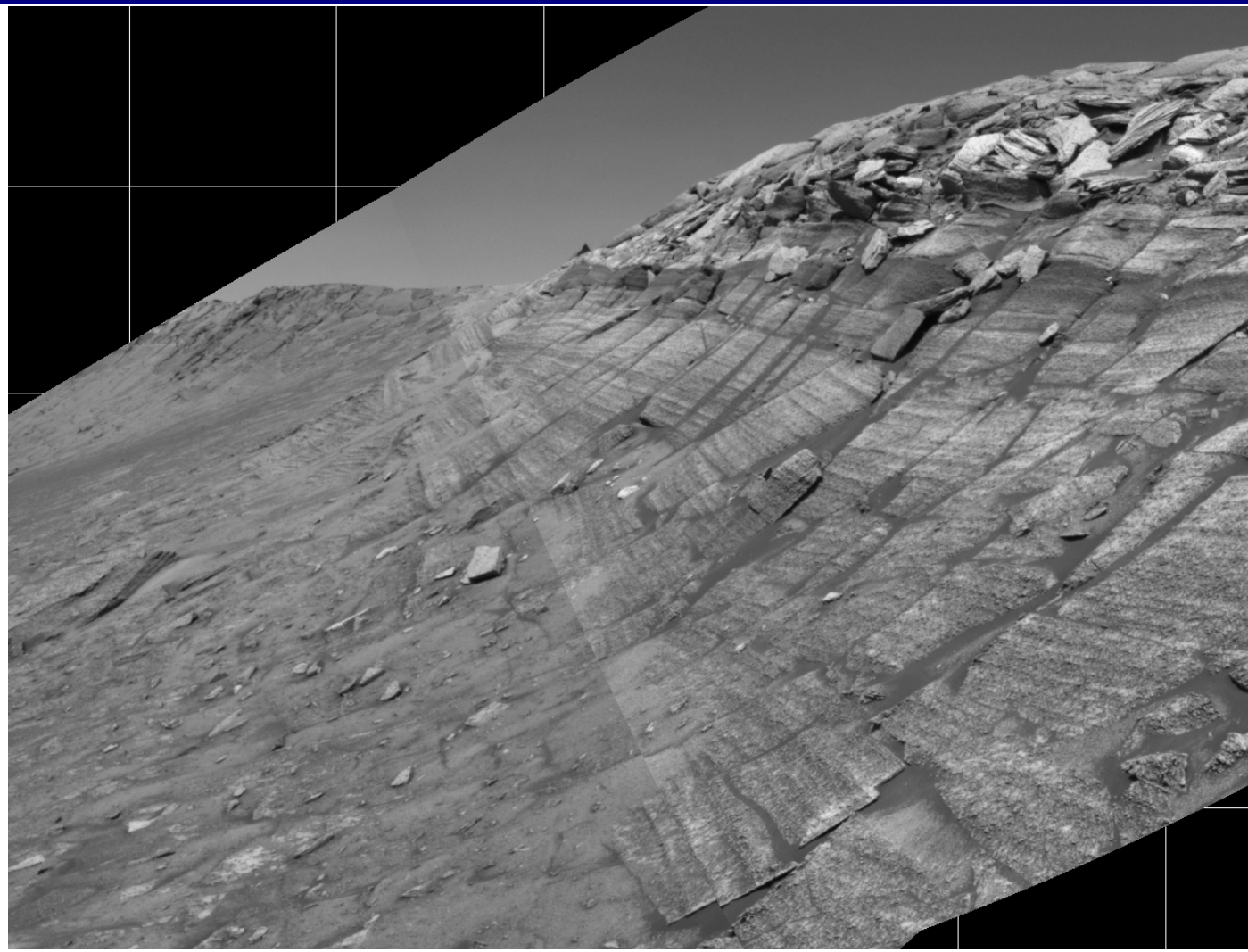


Figure 3. View from Mars, of the Burns Cliff formation inside of the Endurance crater on the Meridiani Planum, taken by the rover Opportunity

Mobility System – Rocker Bogie

- Rocker-Bogie mobility is comprised of 6 wheels, all driven, with the outer 4 steered
- Rocker-Bogie utilizes a differential and linkages to effectively equilibrate the wheel loads during drives
- The first rover to Mars, Sojourner, was also a rocker-bogie vehicle

Figure 4. MER Flight Vehicle 'Spirit' during Integration & Test, shown with 'Marie Curie'

Mobility System – Hardware Assemblies

- Each rover has a left-side and right-side rocker-bogie
- The differential is comprised of two counter rotating planetary gear assemblies, which are connected together by a torque tube
- All elements of the suspension are designed to absorb elastic energy during drive impacts

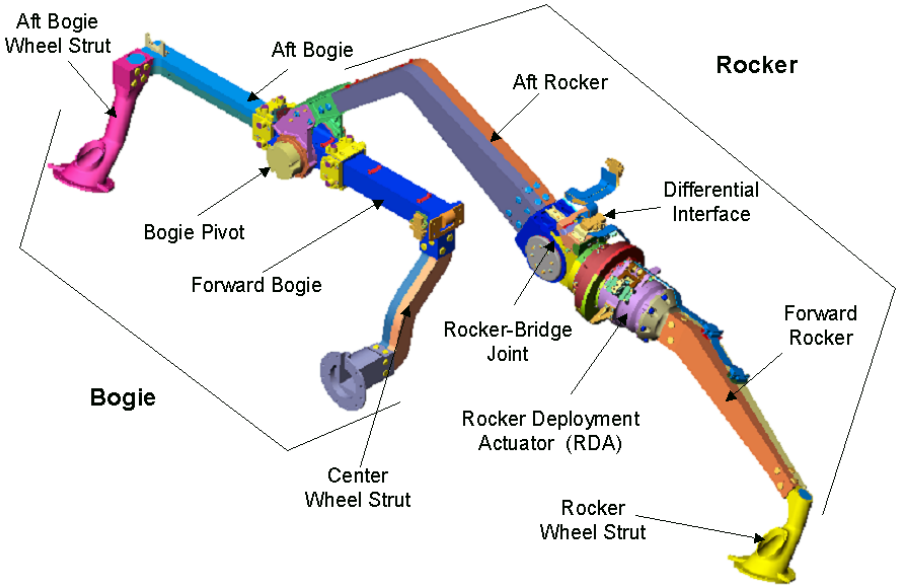
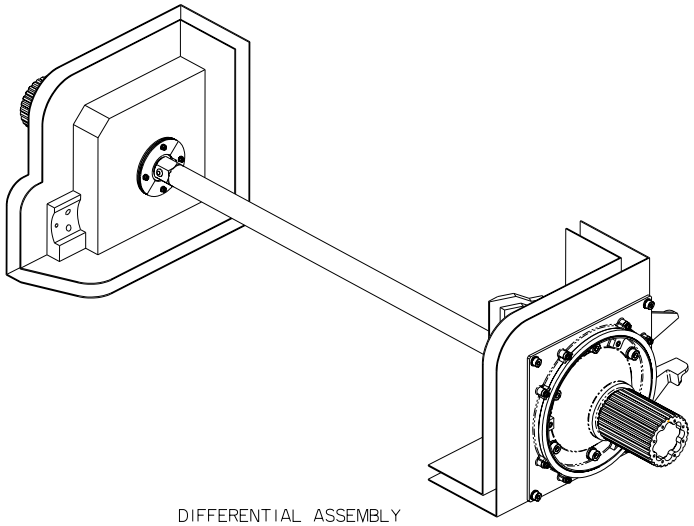
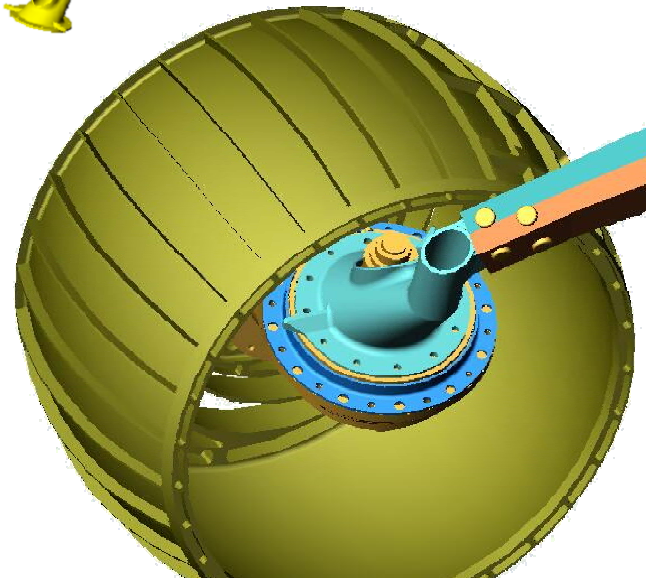


Figure 5. Design Graphics generated from the CAD models in I-deas NX



Wheel and Actuators Assembly



Mobility System – Launch through Egress

- The launch, cruise, and entry-descent-landing systems of MER are similar to those of the Mars Pathfinder project of the mid-1990's
- The main change is the design of the entire spacecraft around a large rover that completely fills the lander
- Once the rover leaves the lander, the lander is dead

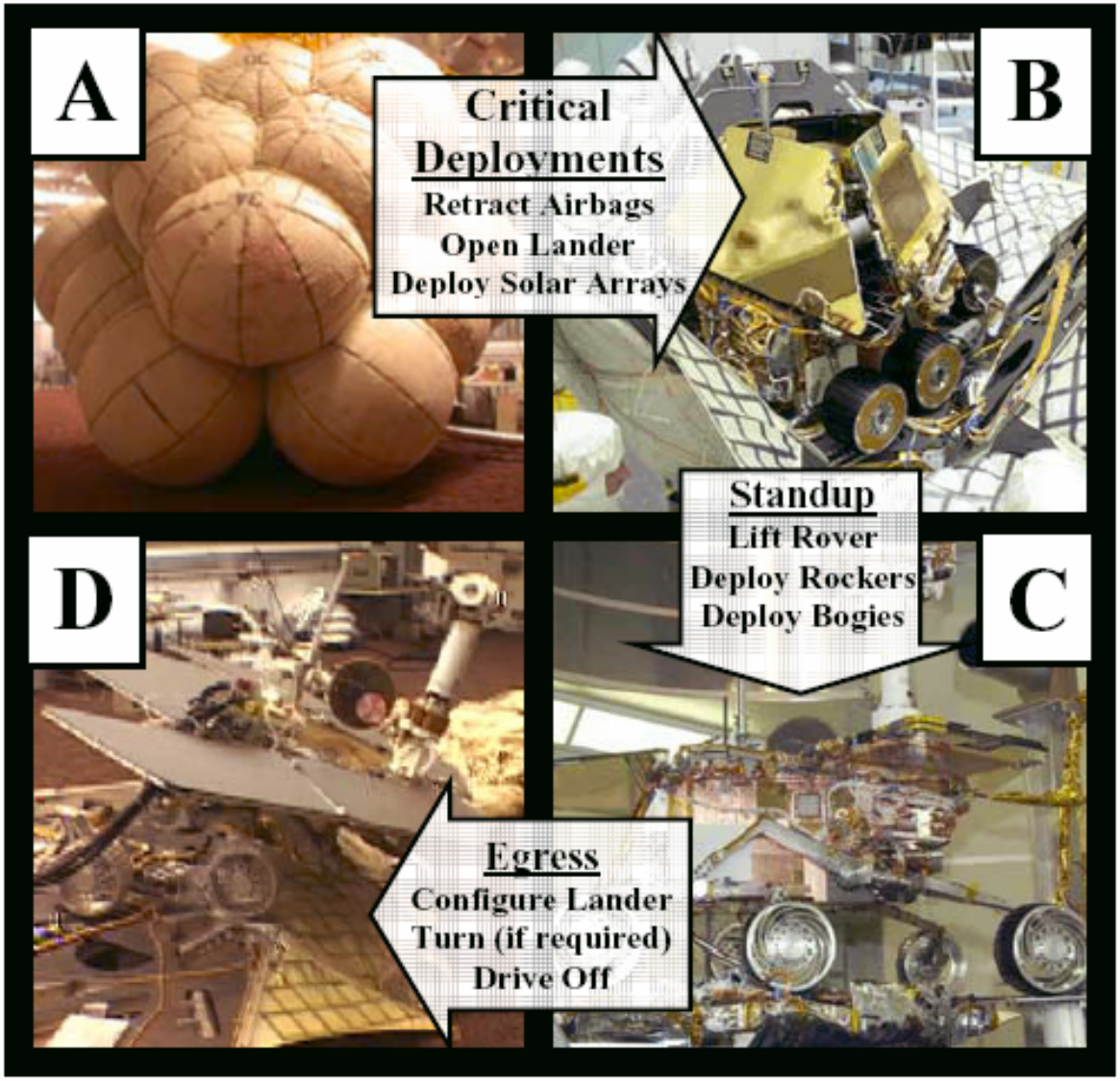


Figure 6

Lander and Rover Deployment

- MER was driven by many extraordinary demands in terms of geometric and mass constraints
- The task of designing the rover, lander, and aeroshell has been compared to “Russian Dolls” that encapsulate each other, with no room to spare
- The result is a system with an extreme number of deployments

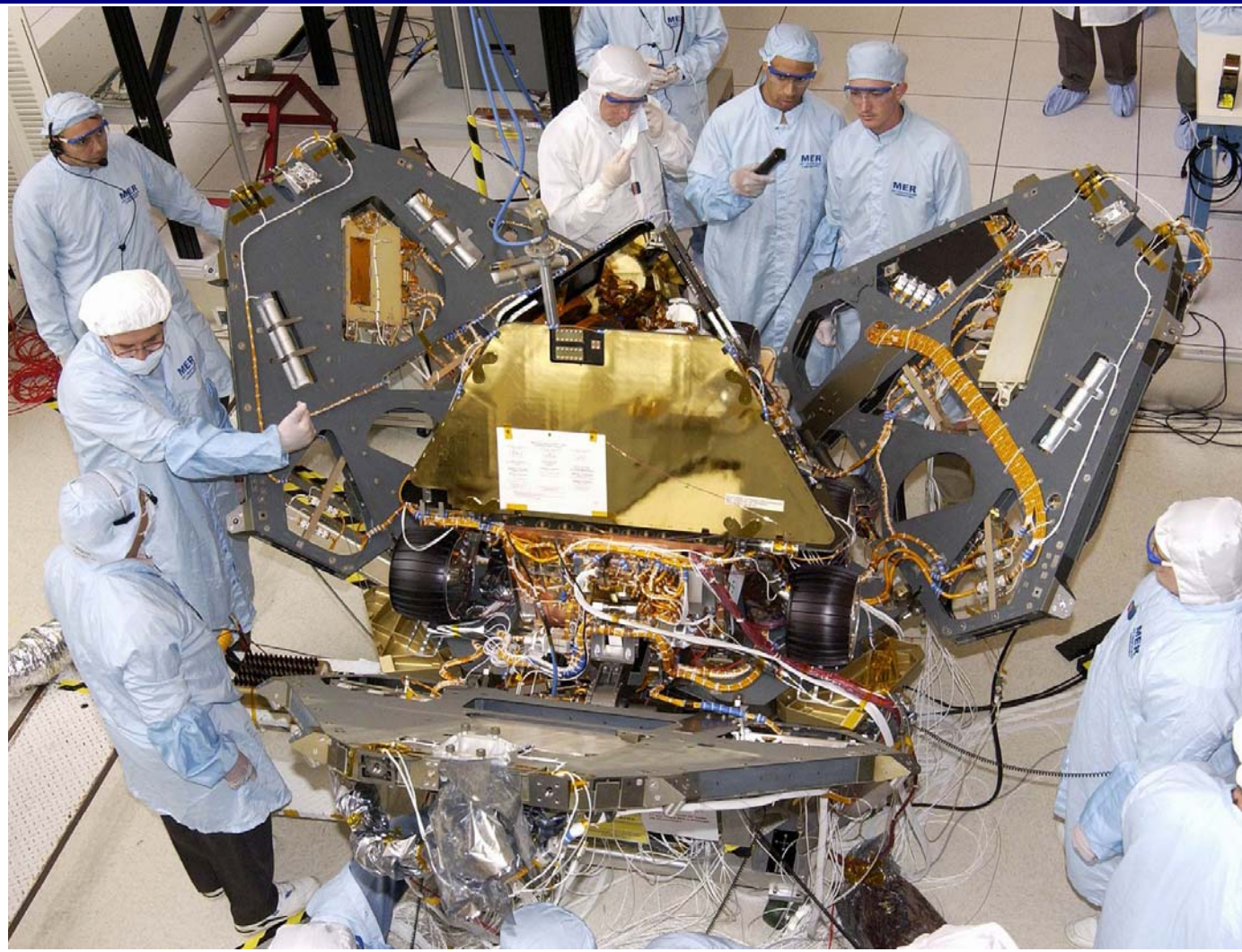
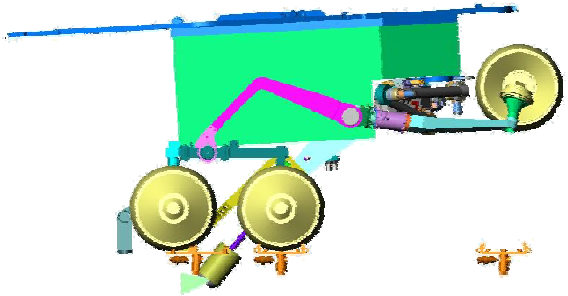


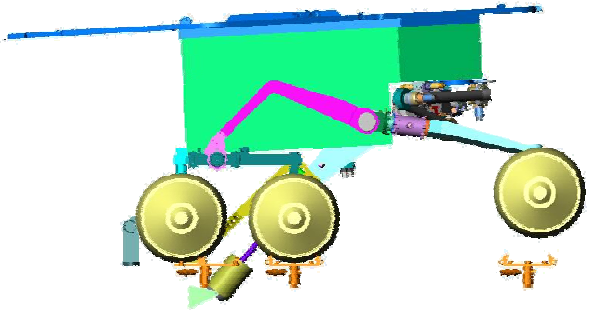
Figure 7. MER Flight Vehicle ‘Opportunity’ during first Integration with the Flight Lander

Rover Design – Mobility "Standup"

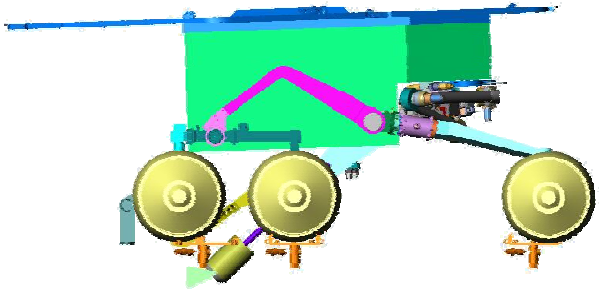
1. Pyro-Release WEB restraints, Pyro-Cut Rover Cables 1 and 2, Pyro-Release Front Wheels



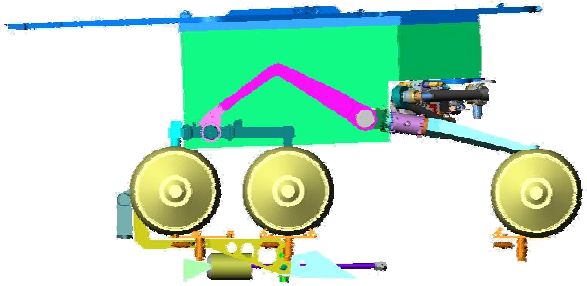
2. Raise the Rover WEB with the Rover Lift Mechanism until the Rocker Bridges latch to the Differential



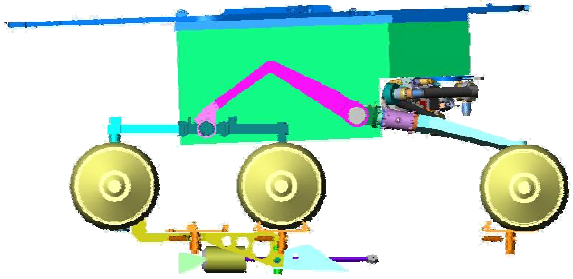
3. Rotate Rocker Arms 180 degrees about the deployment axes until the Rocker Arms latch to the Rocker Bridges



4. Lower the Rover Lift Mechanism until the Front Wheels rest on the Lander



5. Continue to Lower the Rover Lift Mechanism until it separates from the WEB and Stows flat in the Lander Basepetal



6. Pyro-Release Rear Wheels, Deploy the Bogies until they latch, release the middle wheels, Cut Rover Cable 3

Figure 8. Sequence of Mechanical Articulations and Latching for Mobility Deployment, graphics generated from CAD Assembly in I-deas NX

Rover Design – Mobility Steering

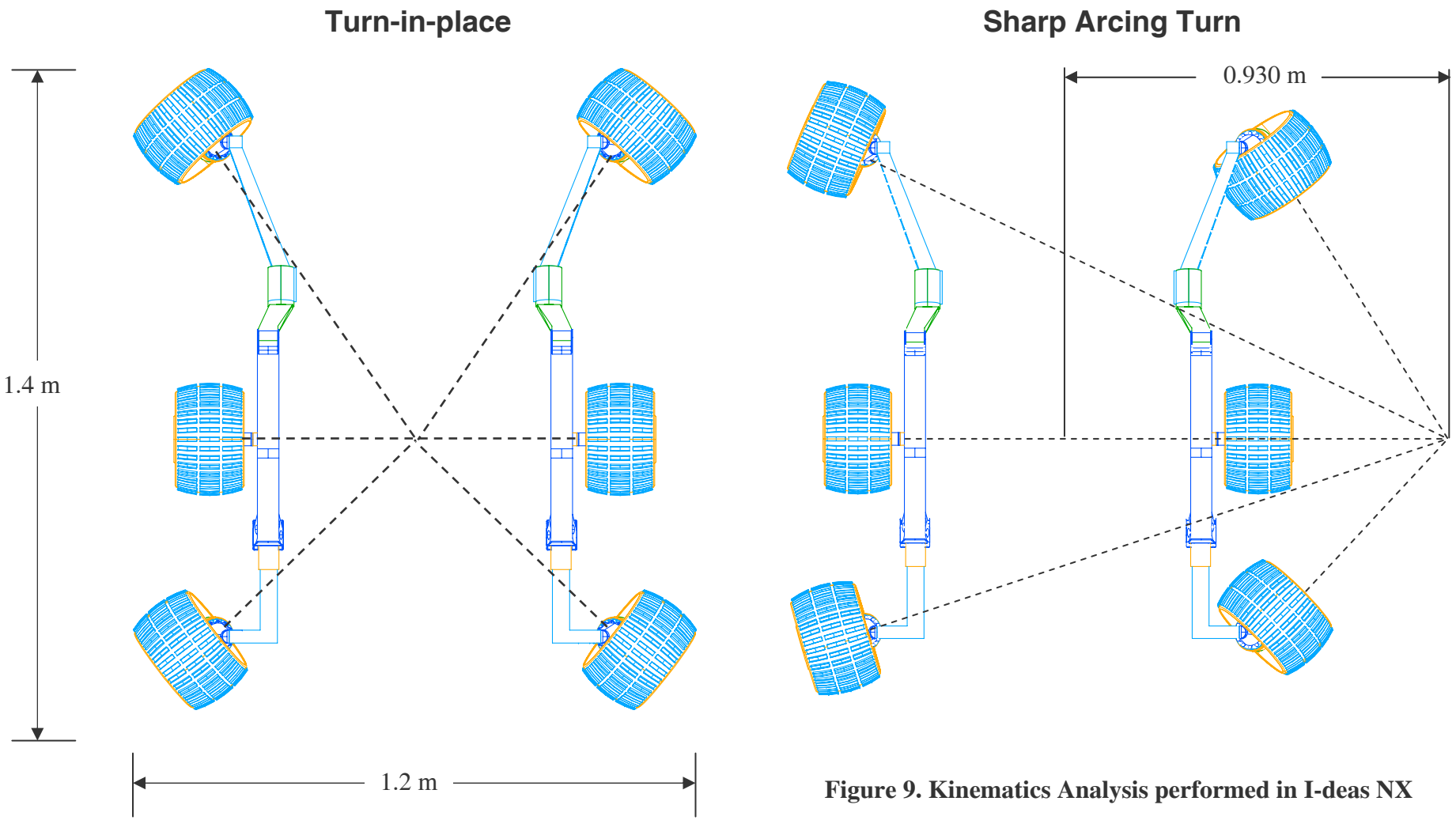
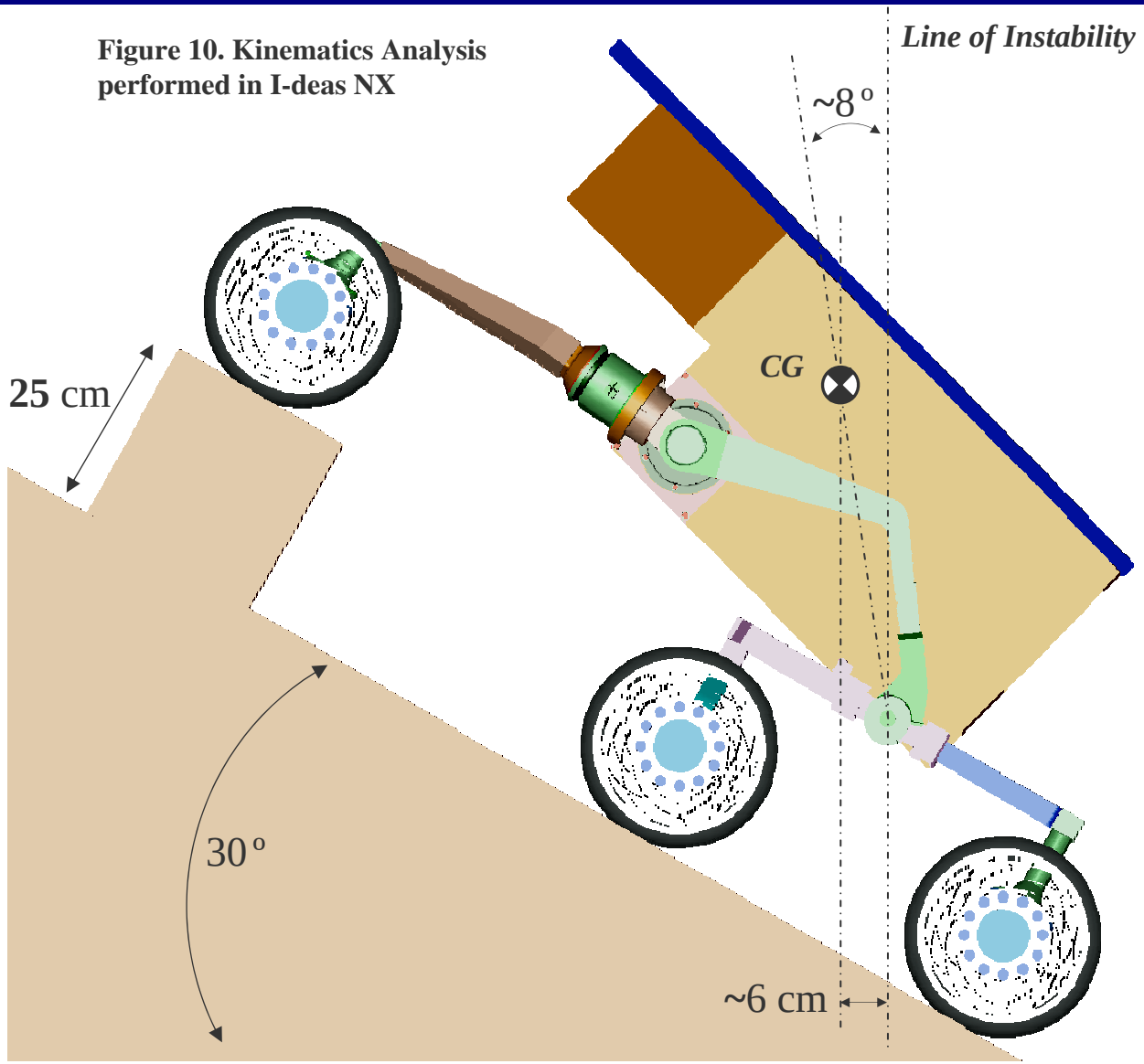


Figure 9. Kinematics Analysis performed in I-deas NX

Rover Design – Vehicle Static Stability

- Because the landing sites chosen for the two rovers were so benign, the initial requirements on mobility were minimal
- Once landed however, the science team overwhelmingly desired to climb hills and craters
- Additional work post-launch, showed the rovers to be much more capable than originally required

Figure 10. Kinematics Analysis performed in I-deas NX



Rover Analysis – Structural Loads

- Traditionally at JPL, design loads for spacecraft initially are enveloped using the MAC
- In addition, from both MPF and MER, airbag landing loads were well characterized at ~31.4 g's plus a rotational component
- But for a very large and heavy rover, traverse loads were a new issue

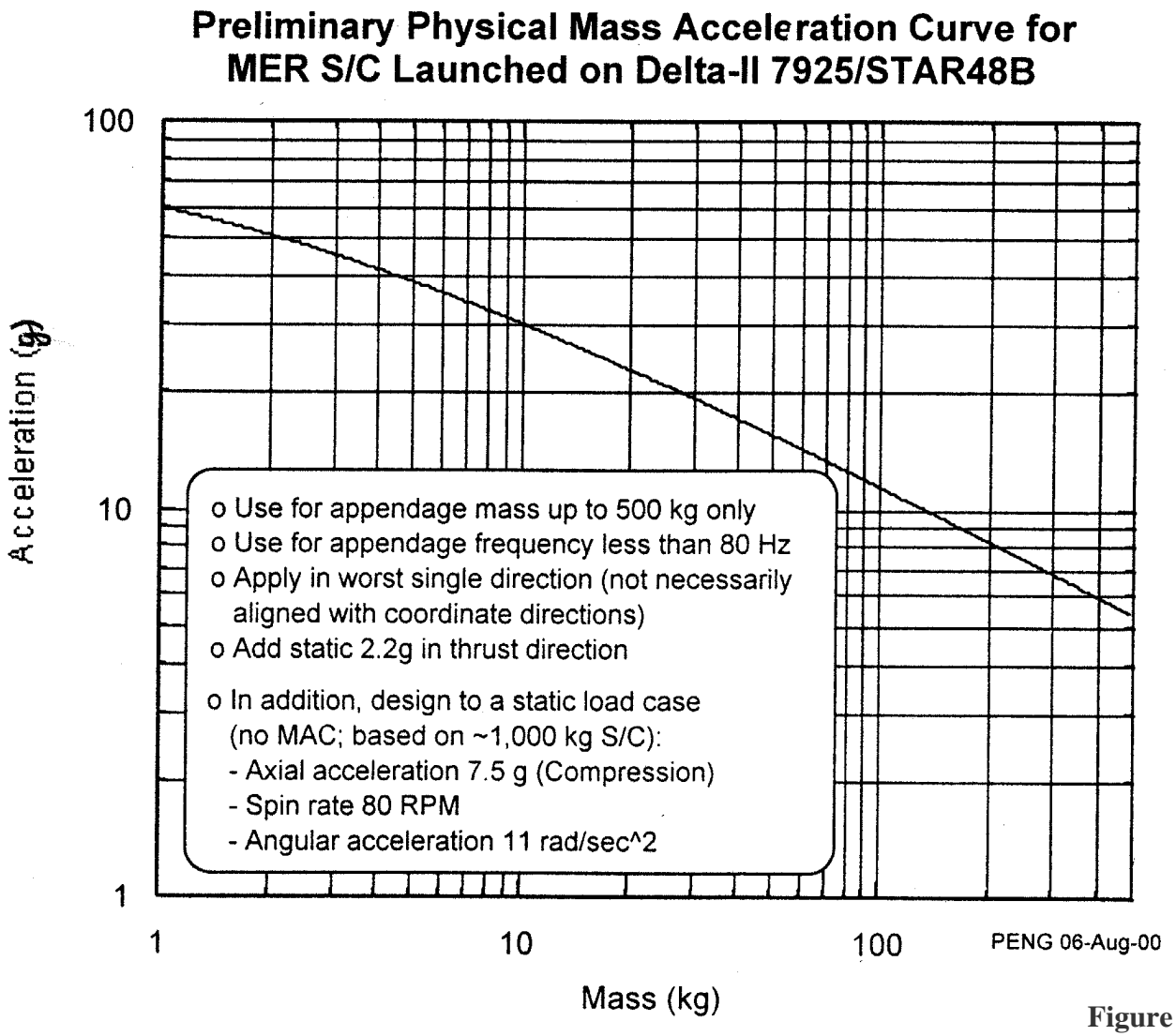


Figure 11

Rover Analysis – Structural FEA

- An FEA was performed on the rover to cover the launch/landing cases
- The FEA analysis was extended as a non-linear FEA to look at the subtleties of the rover deployment and the over-constrained tie-down of the rover to the lander
- In addition, the NASTRAN model of the deployed rover was used as the 'seed' for a dynamic model

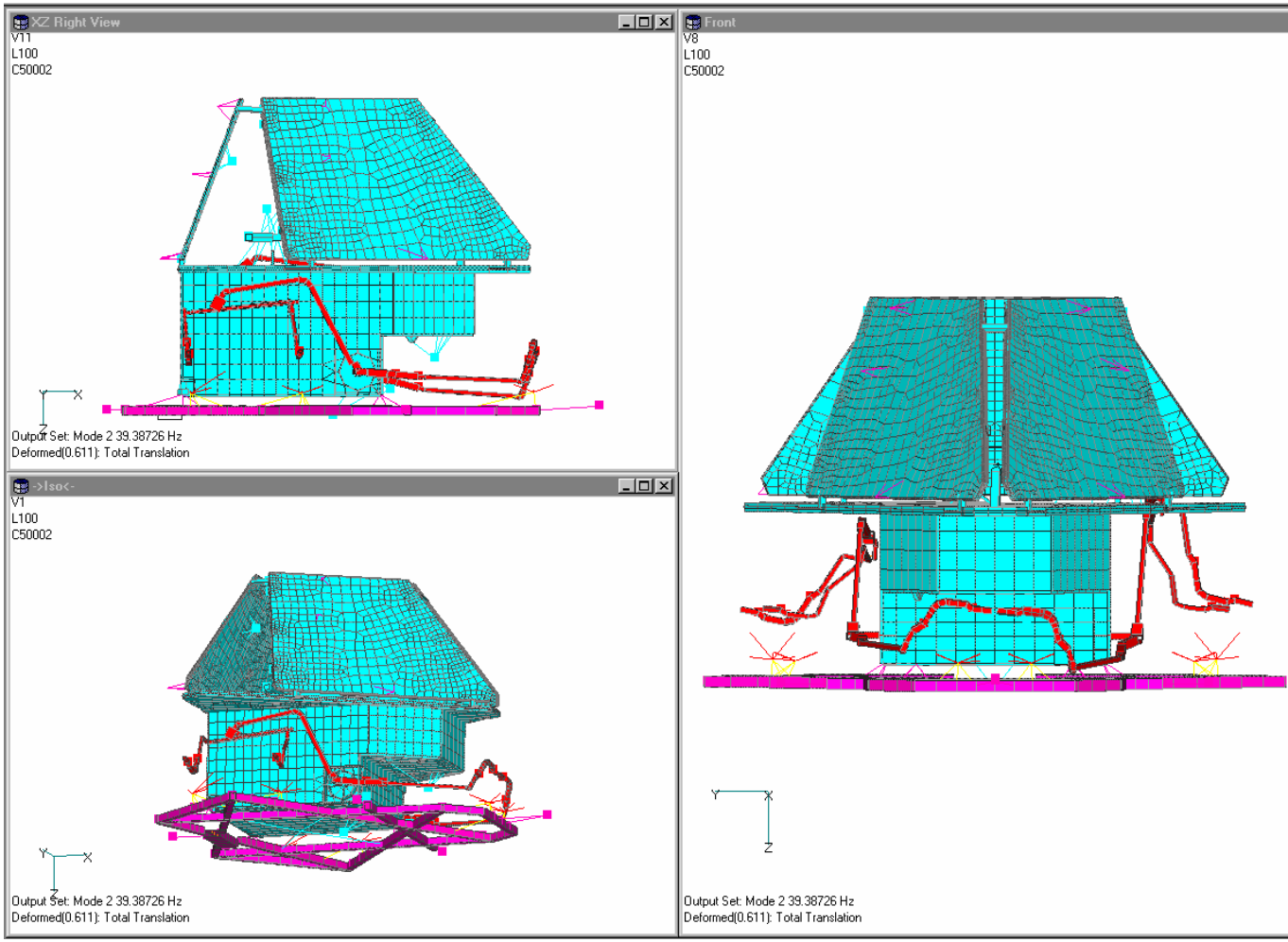
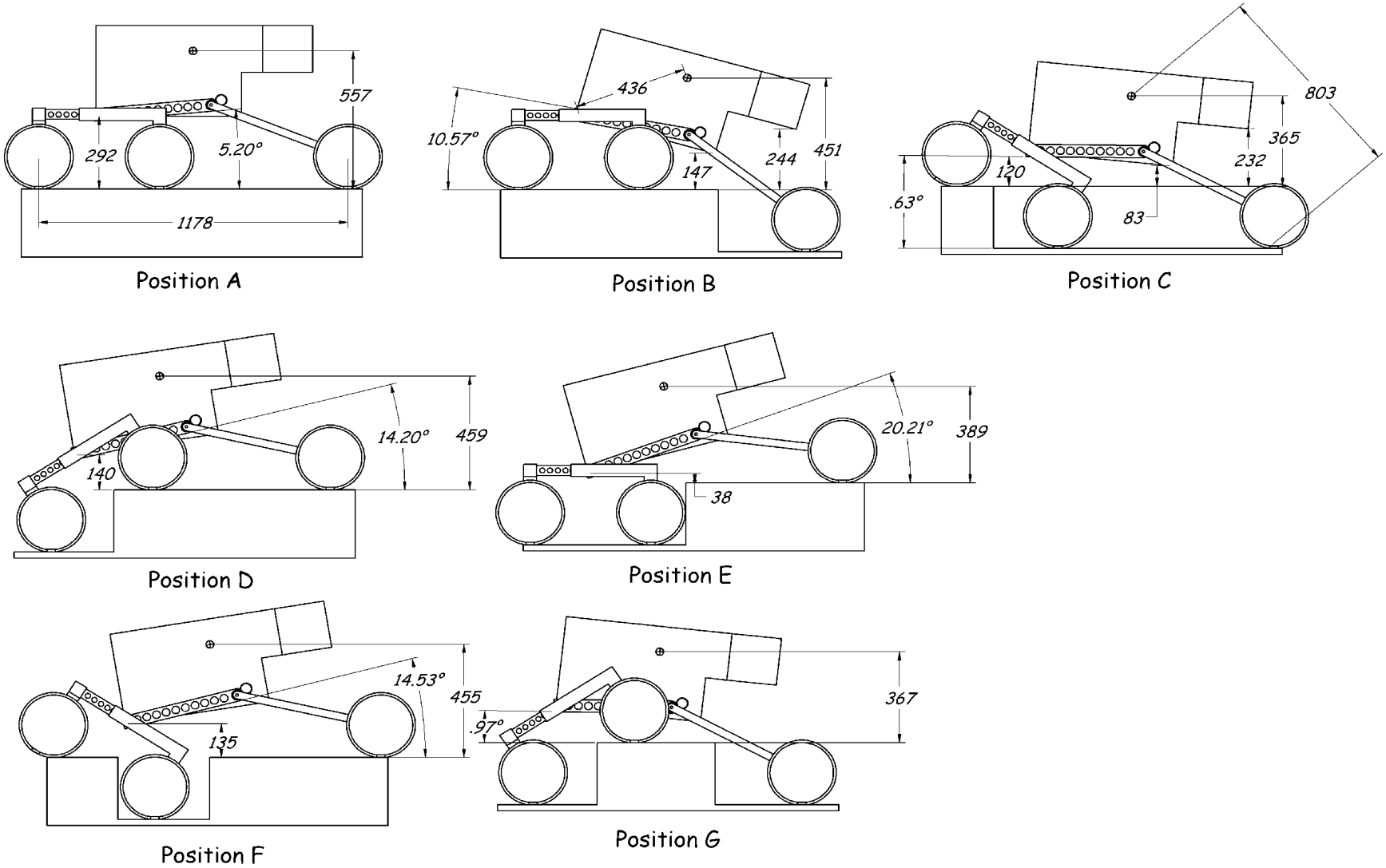


Figure 12. Three Views of the first Mode (39.4 Hz) of the Stowed Rover calculated by NASTRAN

Rover Analysis – Dynamics during Mobility

Figure 13. Set of Planar Drop Cases for Worst-Case Mobility Loads Analysis, analysis performed in I-deas NX



Rover Analysis – Dynamic Model

- Modeling Idealizations :
  - 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

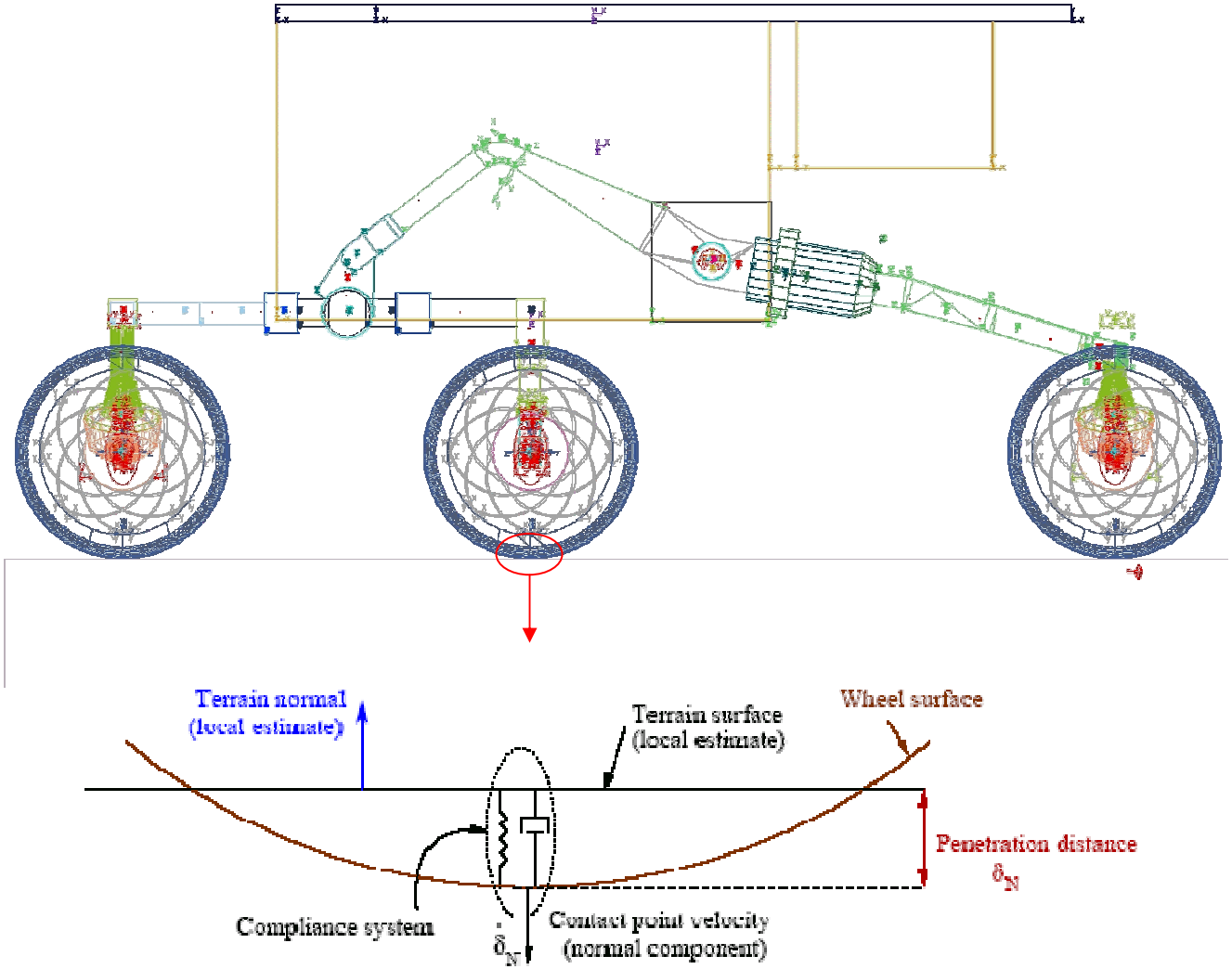
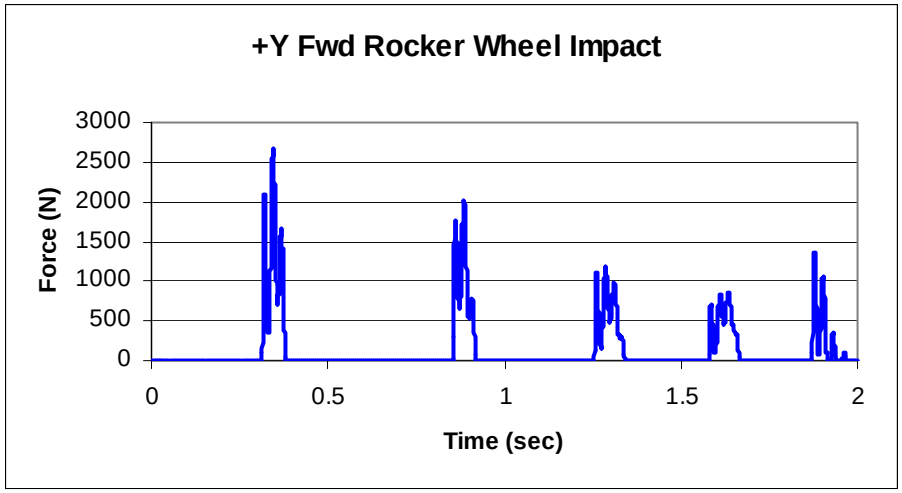


Figure 14. Dynamic Modeling of the MER Rover in MSC.ADAMS

Rover Analysis – Dynamic Simulation

- The initial Dynamic Simulations all represented wheel 'Drop' cases, worst-case scenarios of the rover traversing obstacles at the maximum acceptable limit with the rover falling off the obstacle onto rigid ground

Case AB: Simulated Wheel Impact Time History



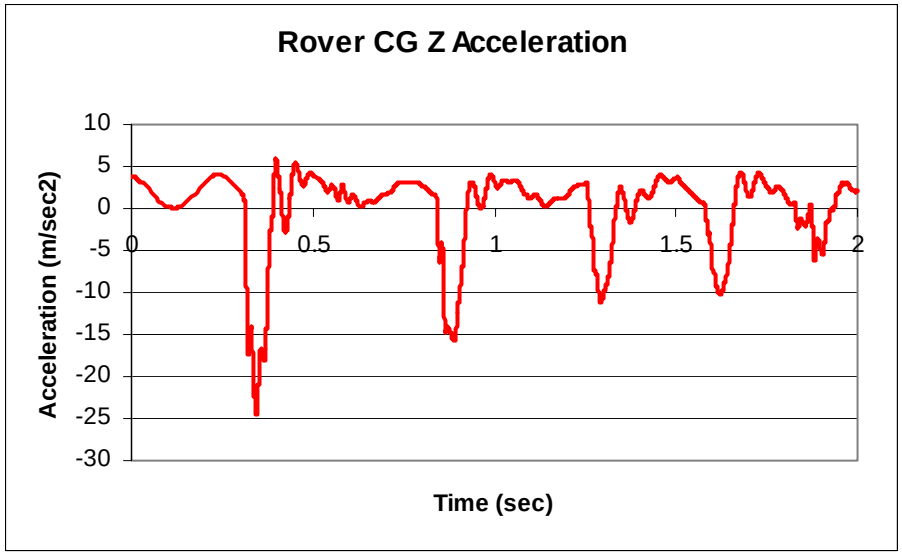


Figure 15

Rover Analyses – Results

- Worst-case mobility loads were determined to be maximum and became the design limit loads for the wheels, mechanism housings, suspension structure, and the differential
- The mobility loads reflected a largest mass rover of 185 kg, which came to be the flight mass, as well as a 10% uncertainty factor to account for suspension structure stiffness differences
- Much of the up-front kinematics of the loads analysis was done using a suite of CAD tools not specifically designed for the task they were ultimately used for

		Load Cases		
Item	**Load Component**	**Liftoff**	**Landing**	**Mobility**
Wheel Vertical Reaction	Fz (lbs)	374	420	600
Torque Tube	Torsion (in-lb)	44	214	1509
Output Shaft	Vrss (lbs)	102	306	692
	Mrss (in-lb)	469	1368	7019
Tip Fitting	Vrss (lbs)	19	59	305
	Mrss (in-lb)	171	662	3452

Drop Testing – Worst Case Mobility Loads

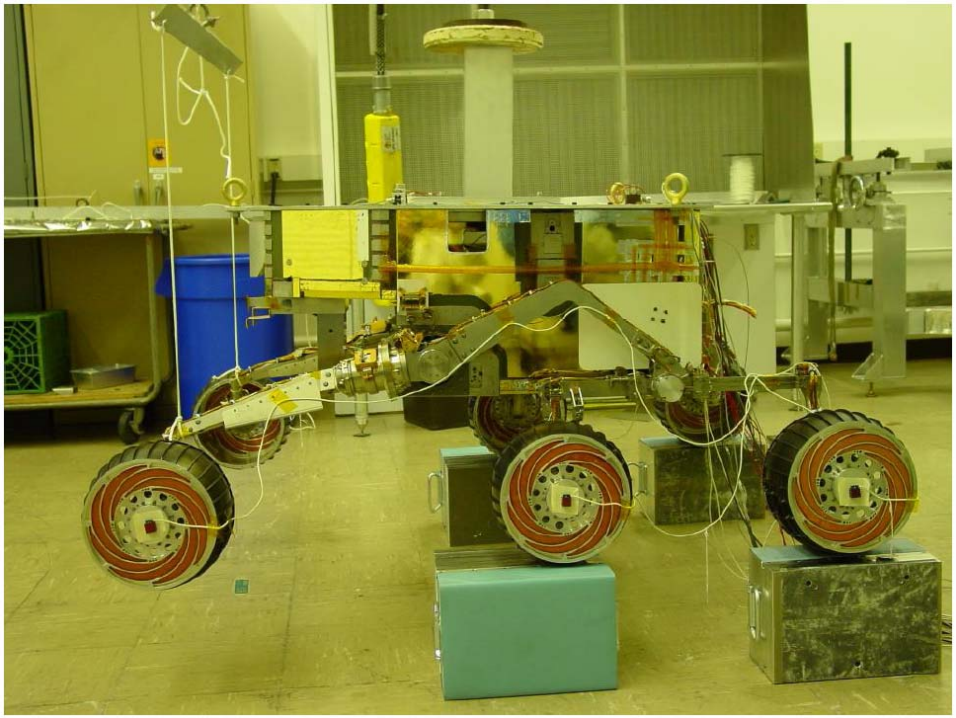
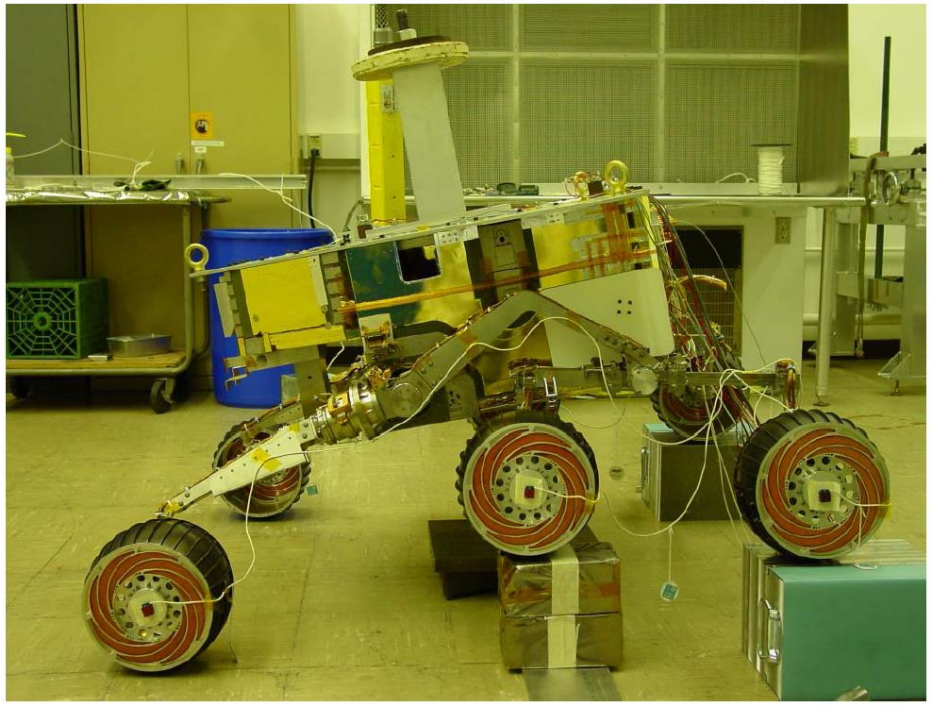
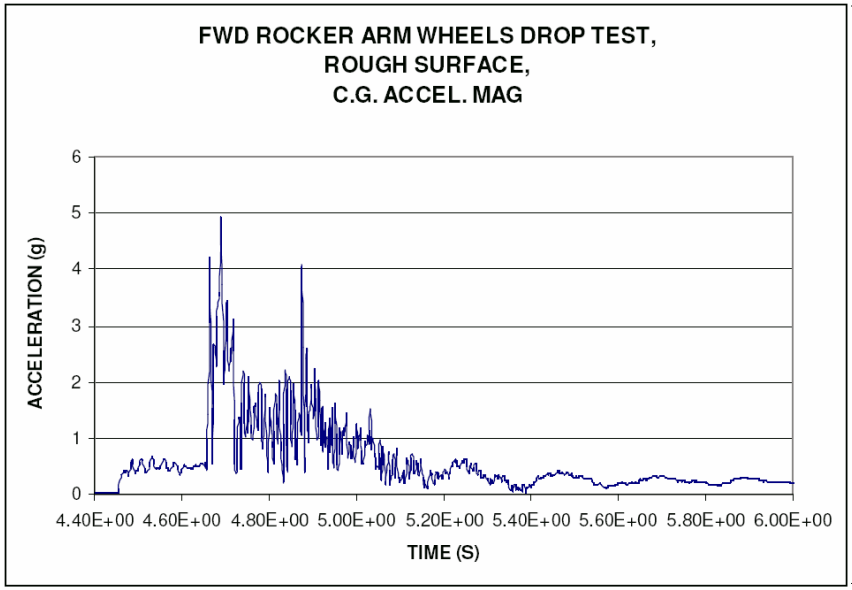


Figure 16. Dynamic Test Model rover (DTM) in Configuration A, prior to release of the two front wheels

Figure 17. Dynamic Test Model rover (DTM) in Configuration B, after the release and impact of the front wheels to the floor



Drop Testing – Results for the AB Case



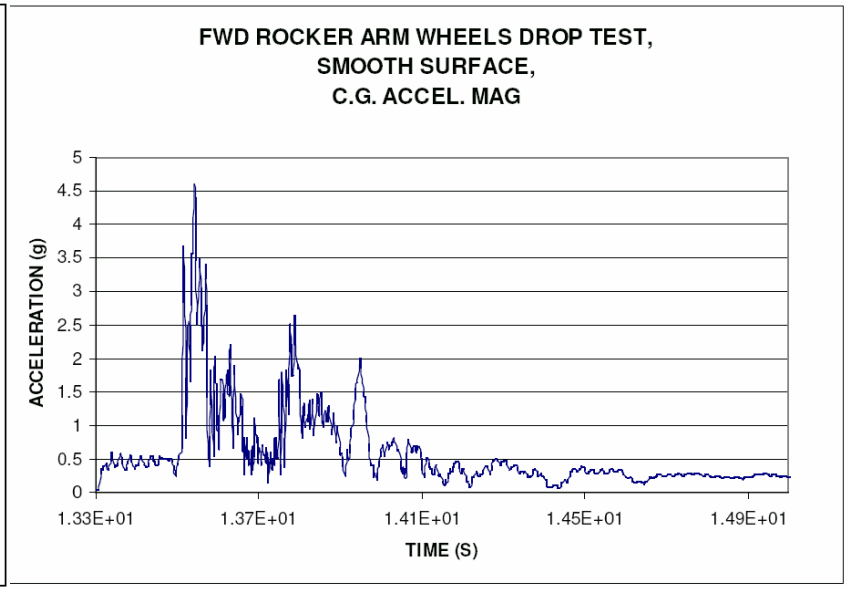


Figure 18. Test Telemetry taken from Accelerometers attached to the DTM rover

Forward Rocker Arm Two Wheel Drop Test Results					
	Web Center of Mass Acceleration				
Impact Boundary Condition	|X Dir.| max (g)	|Y Dir.| max (g)	|Z Dir.| max (g)	Mag. max (g)	ADAMS Mag. Max (g)
Smooth Surface	3.7	2.28	2.75	4.58	4.77
Rough Surface	3.91	3.82	3.36	4.93	*
Driven on ESD Surface	0.96	1.13	0.63	1.26	*

Mobility Testing – Variable Terrain Tilt Platform

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

Figure 19. DTM Rover on the VTTP at a 15 deg slope, climbing a 25 cm obstacle

Mobility Testing – VTTP with Loose Sand

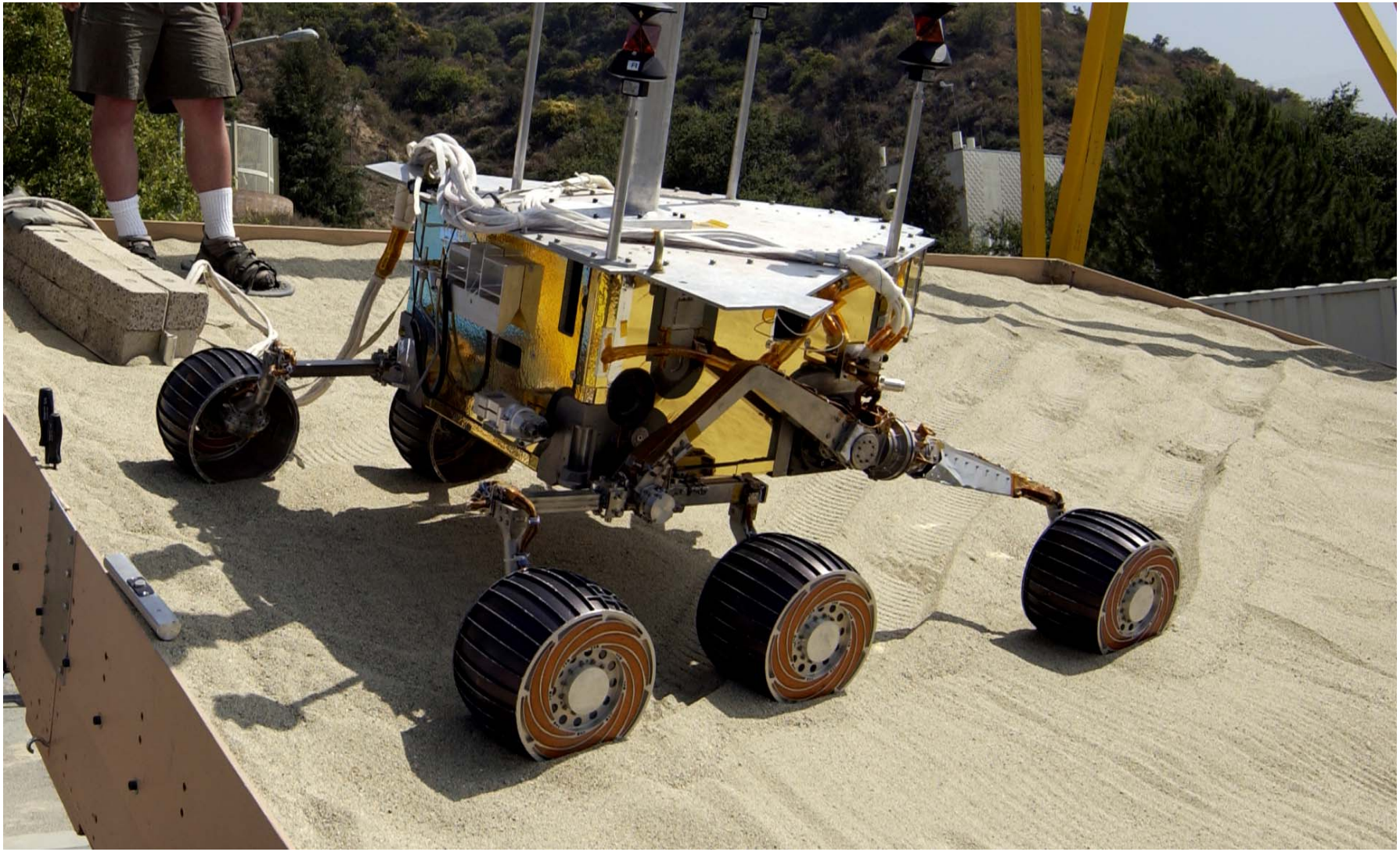
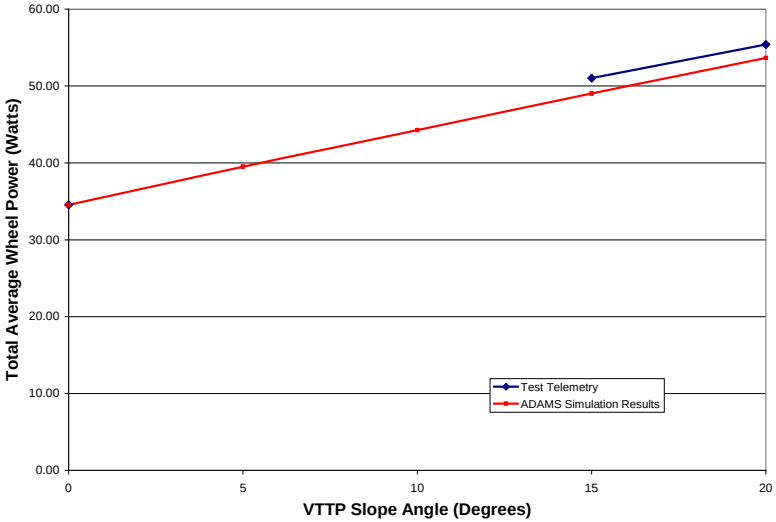


Figure 20. DTM Rover driving cross-slope on the VTTP at a 20 deg slope covered with 20 cm of loose sand

Test-Model Correlation – Driving Case Results

Figure 21. Comparison of Test Results (in blue) against Simulation Results (in red) for the DTM driving up-slope



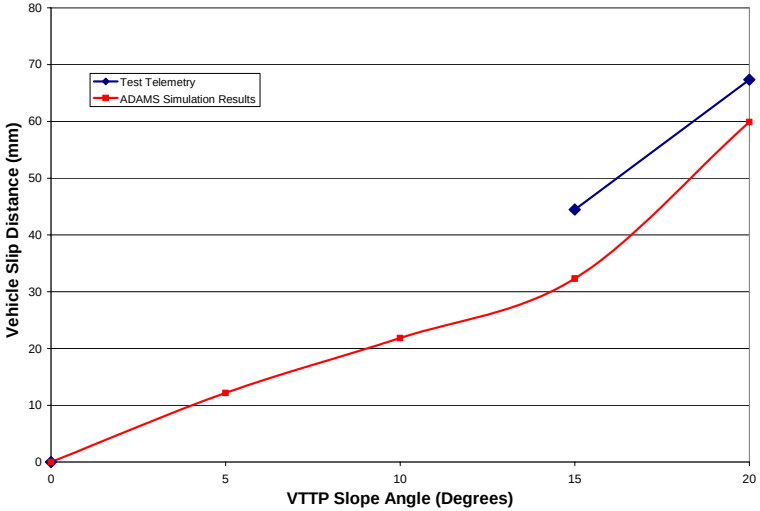
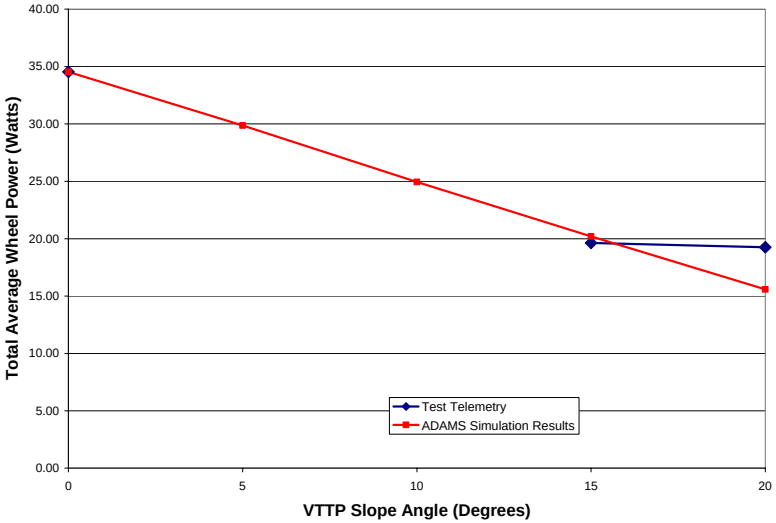
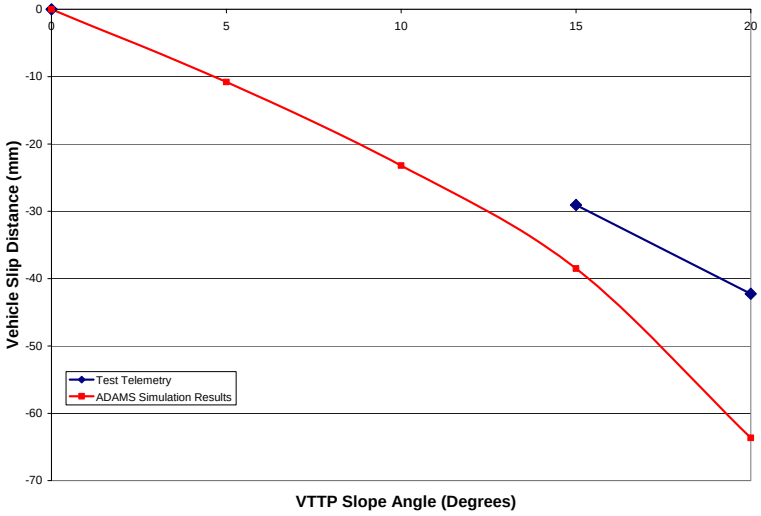


Figure 22. Comparison of Test Results (in blue) against Simulation Results (in red) for the DTM driving down-slope





Results for Driving in Loose Sand

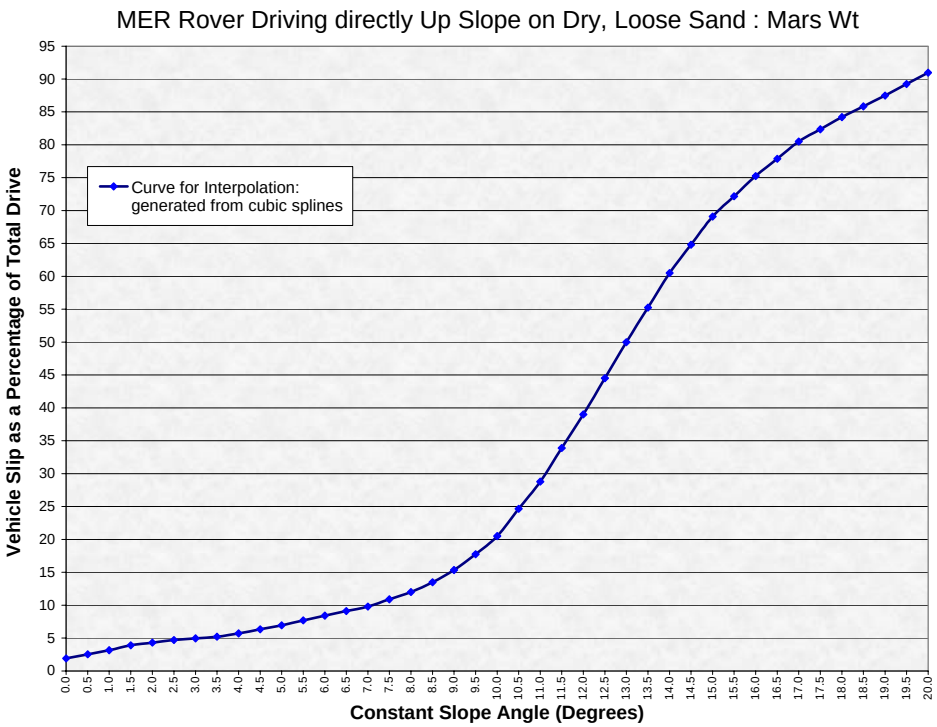


Figure 23

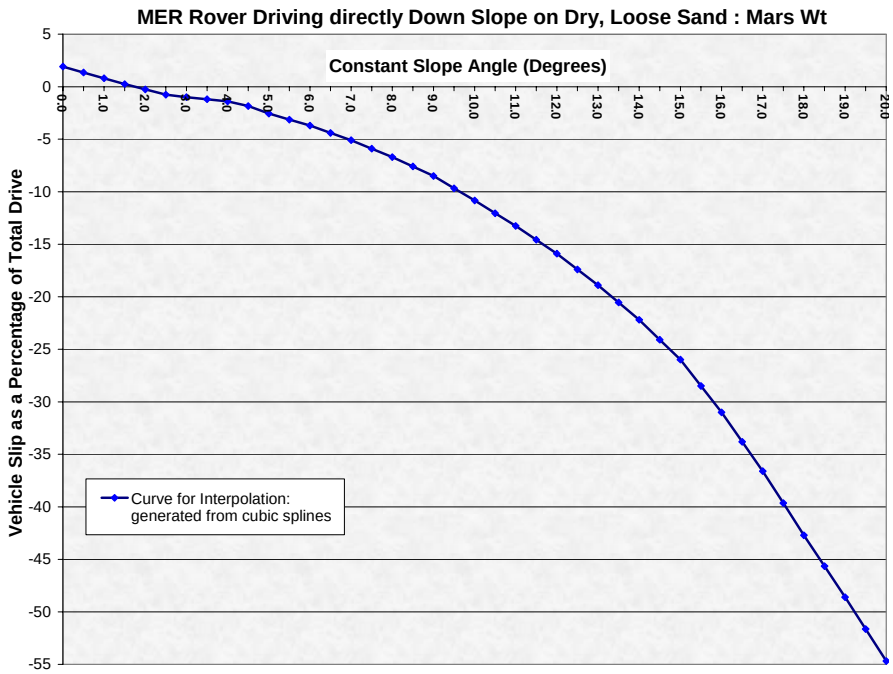


Figure 24

Mobility Performance on Mars - Opportunity

- Analysis showed and Testing confirmed that the rovers were far more capable than as originally 'sold'
- A risk averse project management had to be convinced of the rovers' capability and the inherent safety of the new operations in order to get them approved

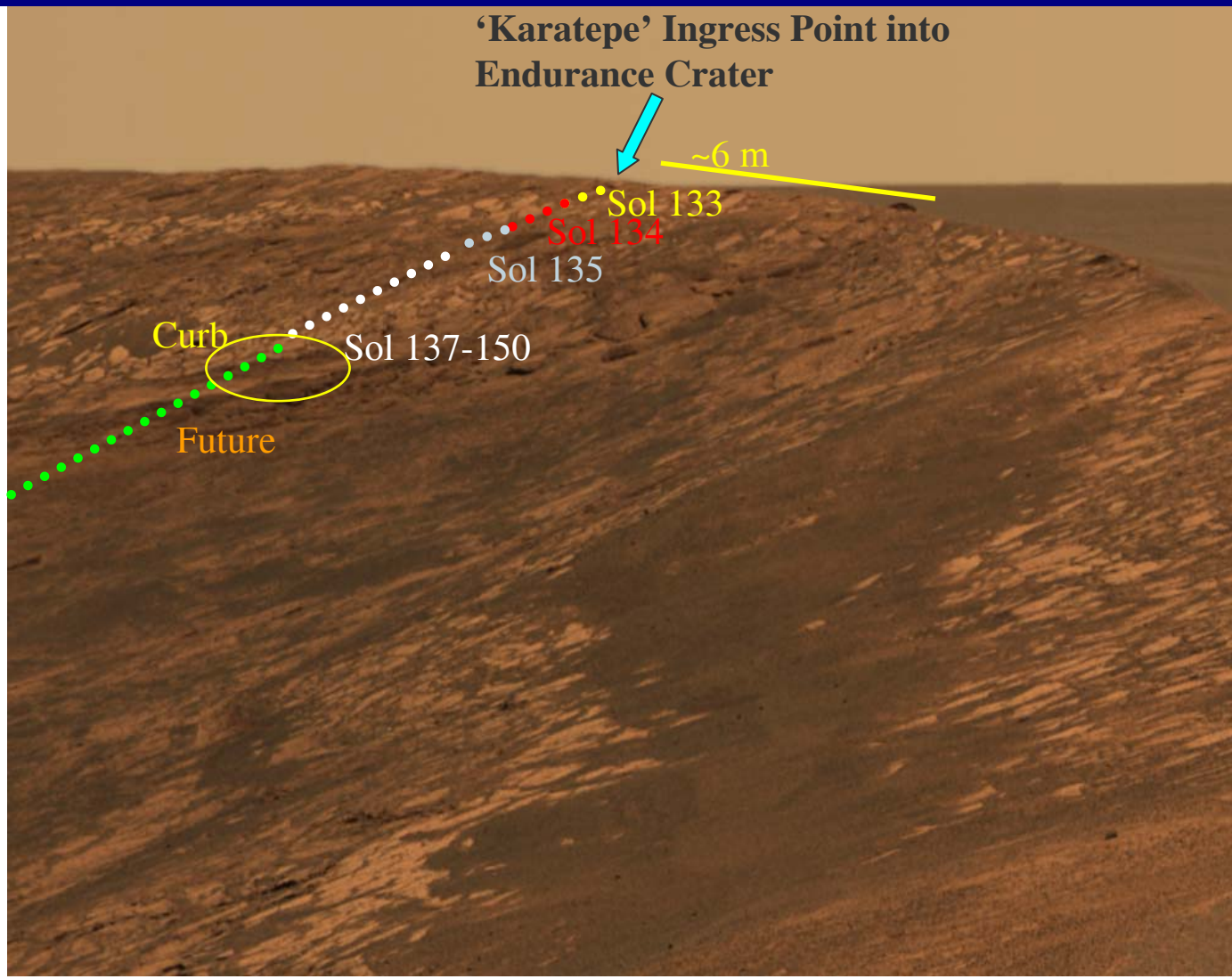
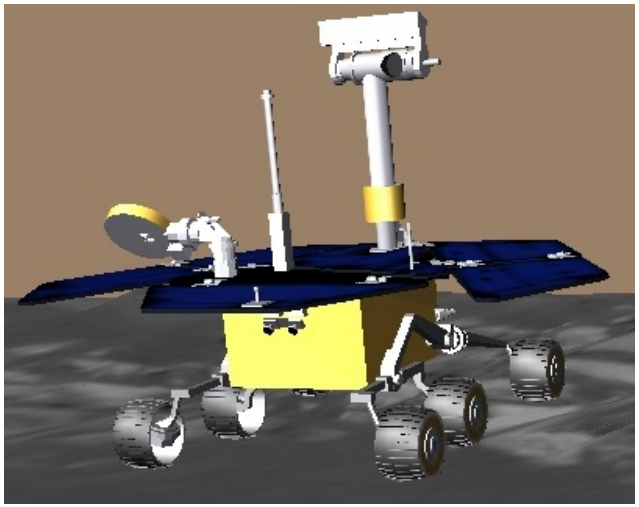


Figure 25. MER Operations Plan for Driving Opportunity into the Endurance Crater

Mobility Performance on Mars - Opportunity

- Rover planners use imaging and kinematic based tools to create 3D meshes of the ground to be driven over, they then plan traverses over the terrain specifying way points to tie the traverse to the safest path
- In all cases these tools for rover navigation were new, in house developments, not related to the CAD tools

Drives Planned in Rover Planner's Tool



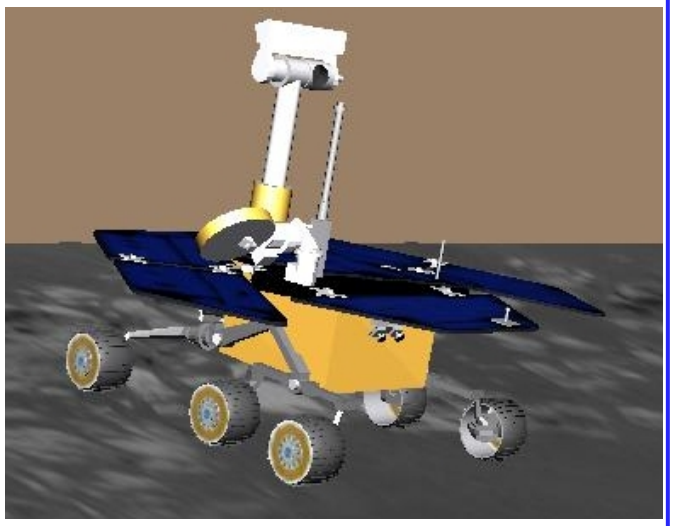


Figure 26

Overall Mobility Performance on Mars

- The rovers have far exceeded their mission requirements in the following ways:
  - Spirit and Opportunity are still working after 800+ sols on Mars (compared to the required 90 sols)
  - Spirit and Opportunity have both traveled nearly 7 km each (compared to the required 1 km)
  - Spirit climbed to the top of a local mountain, called the Columbia hills, during which time the local slopes went as high as 30 degrees; Similarly, Opportunity descended into and then back out of the Endurance crater during which it traversed slopes over 30 degrees (compared to an initial requirement of 20 degrees)
- One area where the rovers performance was not exceptional was in the area of sinkage into soft soil, and the resulting soil work and gross slippage that results; in one particular case, Opportunity was essentially stuck for about a month while testing on the ground confirmed the 99.5% slips required to get out of a 30 cm sand dune

CAD and CAE Lessons Learned

- The MER mission represents only the second semi-autonomous rover mission developed and performed by NASA or anyone else
- Most of the tools (CAD, CAE, testing) utilized were pushed in new and unfamiliar directions, the process itself being an experimental one to arrive at the most appropriate development of Requirements, Designs, and Test/Analysis Verification approaches
- Both MER and MPF were trailblazing missions, and they’re development history will allow the next rover mission, MSL, to follow a much better defined process of design and analysis
- The increased use of integrated and proven tools will make the task of developing future rovers more efficient, reducing project and mission risk, and costs

Acknowledgements

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