



**JPL**

*Mars Exploration Rover*

# Mars Exploration Rover: Launch, Cruise, Entry, Descent and Landing

Rob Manning

- EDL Manager

Mark Adler

- Spirit Mission Manager

Jim Erickson

- Project Manager

Jet Propulsion Laboratory

California Institute of Technology

NASA

Work presented here was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration





# Launch Plans



JPL

*Mars Exploration Rover*

- 2003 is a great time to go to Mars - best in 32 years.
- 21 days between landings, 10 deg Earth elevation
- Optimum: June 4 – 24th
- Goal was to get 99% probability of getting a launch with 2 launch opportunities (two azimuths) per day and to keep the probability of a commanded shutdown < 99%.
- Actually needed 21 days to get 99% probability of getting off the ground (added at the end). We sacrificed (added) some probability of a commanded shutdown (<99%) by extending window to 20 days.
  - MER-A:
    - Delta II 7925
    - May 30th-June 19th,
    - C3 of 9.4 (km/s)<sup>2</sup> w/ 1077 kg
  - MER-B:
    - Delta II 7925H
    - June 25th-July 15th,
    - C3 of 17.0 (km/s)<sup>2</sup> w/ 1081.5 kg



# Launch Reality



JPL

*Mars Exploration Rover*

- Late analyses delayed first (Spirit's) launch to June 8
  - Ballast removal strategy was quickly developed to squeeze a couple of days onto the end of the launch periods.
- Spirit launched the morning of June 8 after being further delayed by thunderstorms.
- Opportunity's first launch attempt was on June 29 but a boat in the range scrubbed the launch.
- Inclement weather followed by launch vehicle solid rocket insulation repairs followed by flight termination system battery replacement delayed launch further.
- Again on the evening of July 7 all was ready.
- However 8 sec from launch and oxygen valve failed to close resulting in an automatic scrub.
- The problem was resolved and all was readied for the second daily launch azimuth.
- Finally at 11:18 pm EDT on July 7, Opportunity was launched.



# Cruise



JPL

*Mars Exploration Rover*

- Vehicle was well designed for “quiescent cruise” – 2 rpm spinner w/ balanced thrusters.
- Seven trajectory correction maneuvers were planned.
- Despite an enormous amount of work to plan and prepare for these maneuvers, Spirit executed only needed to perform 4 of them and Opportunity only needed 3.





## Lots of other things to do



JPL

*Mars Exploration Rover*

- Attitude Control System & Propulsion characterization
- Camera Checkouts
- DDOR (Delta Differenced One-Way Ranging) Passes
- Flight Software load for EDL and Surface (December)
- HRS (Heat Rejection System) maintenance
- IMU, RAS & UHF checkouts
- Science Instruments Health Checks
- Lander Battery Checkout & Depassivation
- Mini-TES temperature sensor calibration
- ACS attitude maintenance turns
- Cruise solar array switching
- Post-launch Spin down
- Sun sensor calibration



# Cruise Problems



JPL

*Mars Exploration Rover*

- Record breaking solar flares Oct 28, '03
  - Magnitude X43
  - Star scanner noise
    - reinitialized ACS
  - Concern about CPU memory device corruption
    - power cycled CPUs on both rovers
- Thruster fuel line overheating
  - Needed to re-program the set-points
- Lander electronics SEUs
  - The same ones that fire the pyros during EDL.
- Mössbauer anomaly
  - Didn't work in zero gravity



# Site Selection



JPL

*Mars Exploration Rover*

- Fully autonomous EDL system
  - but it can not actively avoid surface hazards
- Primary mode of hazard avoidance was site selection
  - Elevation, latitude, rocks, slopes, dust, winds
  - Used MGS data extensively, also Viking (IRTM) Odyssey (THEMIS)
- Environmental data was folded into detailed end-to-end EDL simulation that allowed the team to calculate the probability of landing within the airbag's capability envelope.
  - Winds
- Prior to launch Meridiani looked very safe but Gusev looked marginal.
  - Gusev's winds combined with the hills and etched terrain in the area made it much less safe than Meridiani.



# Targets



JPL

*Mars Exploration Rover*

- At launch we targeted MER-B (Opportunity) to Meridiani
  - Safest and 1st choice for science.
  - We wanted to get Meridiani later in the season to maximize the solar energy in the first 90 sols.
- While Gusev was the next best science target MER-A (Spirit) was initially targeted to midway between Elysium and Gusev.
  - Elysium was safest, but also not nearly as interesting.
- Gusev had not yet been shown to be sufficiently safe to land.
  - Post-launch Airbag landing capability testing and further refinements in the landing software demonstrated that the system was indeed capable of landing at Gusev safely.
  - By late Summer of '03 Spirit changed course toward Gusev.



# New Challenges During Approach



JPL

*Mars Exploration Rover*

- In late Dec of '03 a regional dust storm near Ares Valles quickly affected the upper air temperature over all of the mid latitudes of Mars.
  - Density was extracted from the MGS TES temperature profiles.
  - The density in the upper atmosphere at both landing sites (in the region above parachute opening) thermally expanded and became less dense.
  - However the lower atmosphere density remained high.
- This forced a change in the parachute deployment parameters.
  - We raised the deployment dynamic pressure targets to get more margin on our timeline between parachute opening and landing.

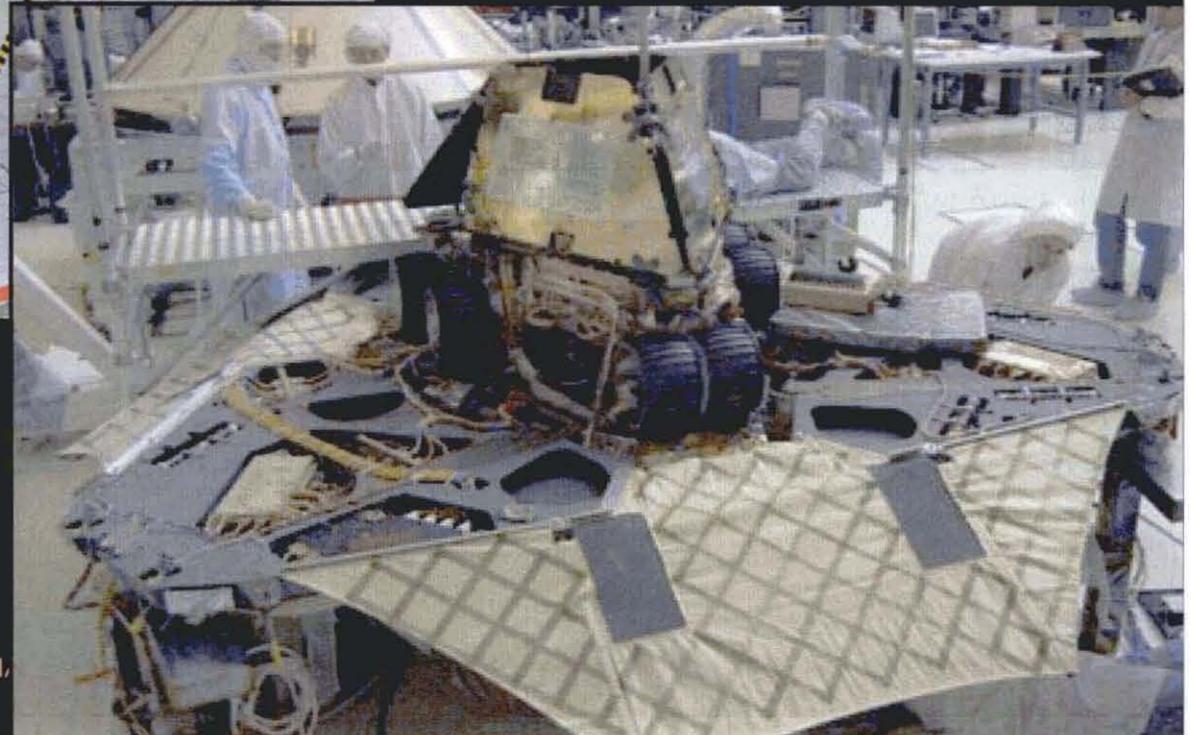
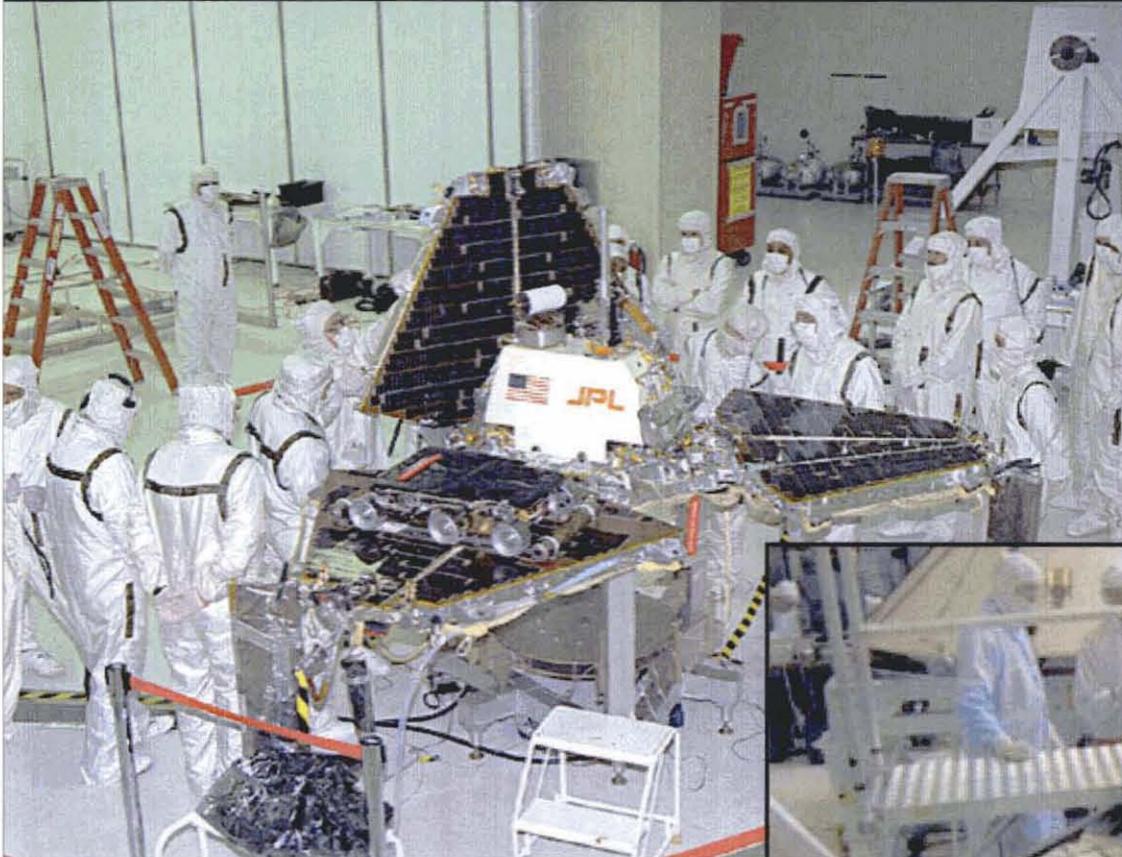


# Faster-Better-Cheaper Parentage



**JPL**

*Mars Exploration Rover*





# Entry, Descent & Landing (EDL)



JPL

Mars Exploration Rover

Entry Turn & HRS Freon Venting: E- 100 min & E- 70 min

Cruise Stage Separation: E- 15 min

Entry: E- 0 s, 125 km, 5.7 km/s,  $\gamma = -11.5$  deg.

Parachute Deployment: E+ 246 s, 7.6 km, 410 m/s

Heatshield Separation: E+ 266 s

Lander Separation: E+ 276 s

Bridle Deployed: E+ 284 s

Radar Altimeter Ground Acquisition: L- 30 s, 2.4 km

DIMES images taken @ 2 km, 1.7 km, & 1.4 km

Airbag Inflation: ~310 m, L - 9.0 s

RAD & TIRS Firing: L- 7 s, ~150 m, 80 m/s

Bridle Cut: L- 3 s, ~20 m

L = Landing: ~E+360 s

Deflation: L+20 min

Roll-Stop: L+10 min

Airbags Retracted: L+69 min

Landing Times (Mars local solar time)

MER-A: ~2:00 PM

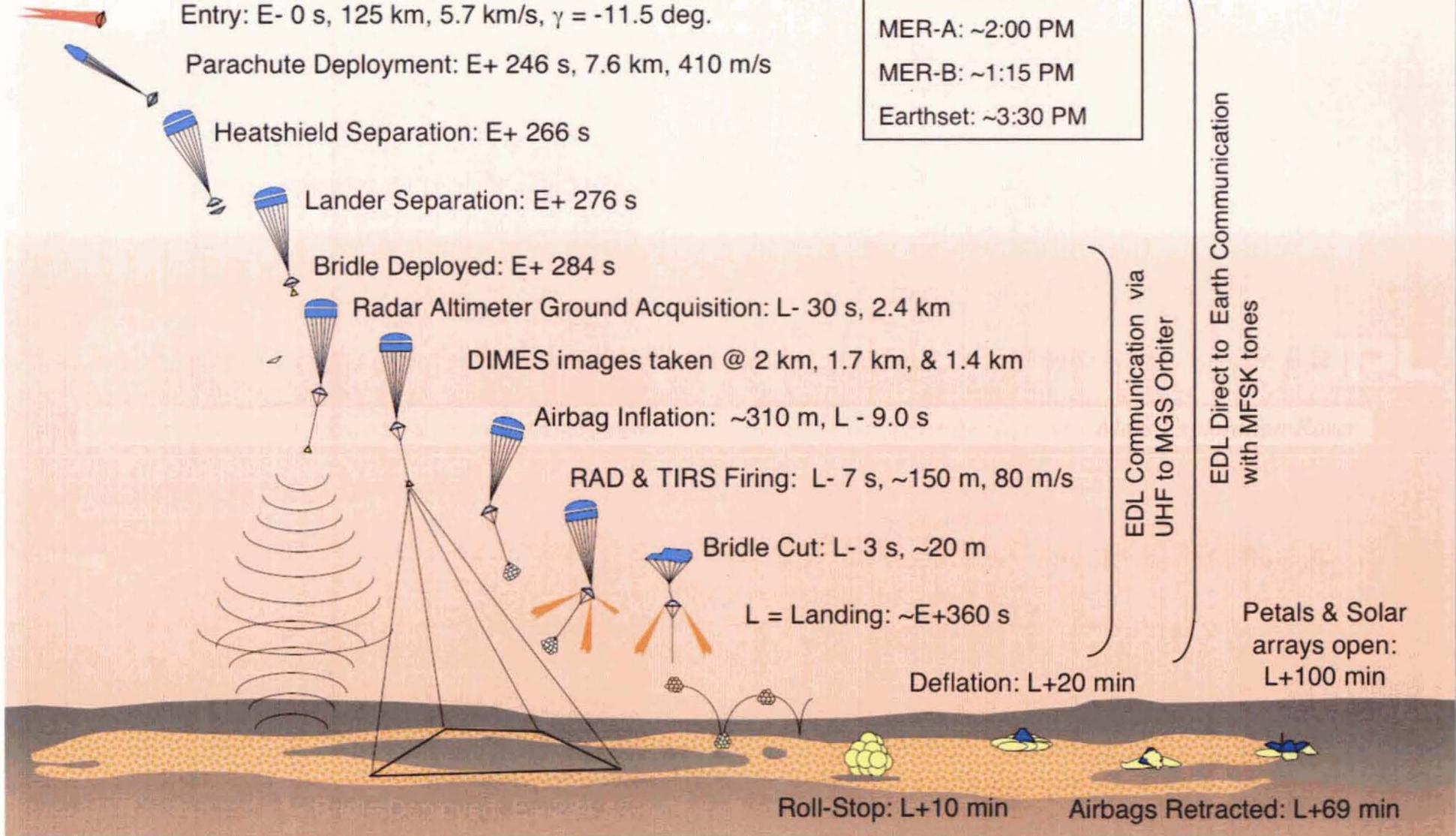
MER-B: ~1:15 PM

Earthset: ~3:30 PM

EDL Communication via UHF to MGS Orbiter

EDL Direct to Earth Communication with MFSK tones

Petals & Solar arrays open: L+100 min





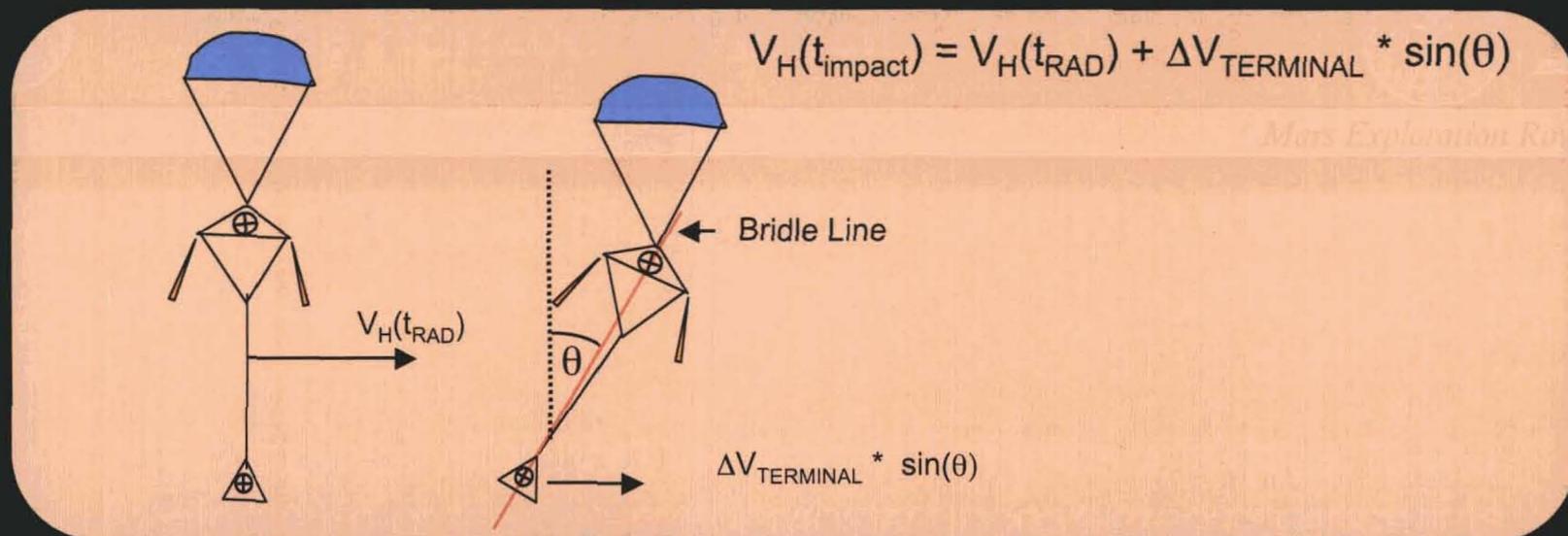
# The Horizontal Velocity Problem



JPL

Mars Exploration Rover

- Two Major Sources of horizontal velocity at touchdown
  - Wind shear
  - Sustained winds
  - The horizontal velocity at the time of first impact is equal to the (vector) sum of the two major mostly uncorrelated components.





# A Partial Solution to the Wind Problem

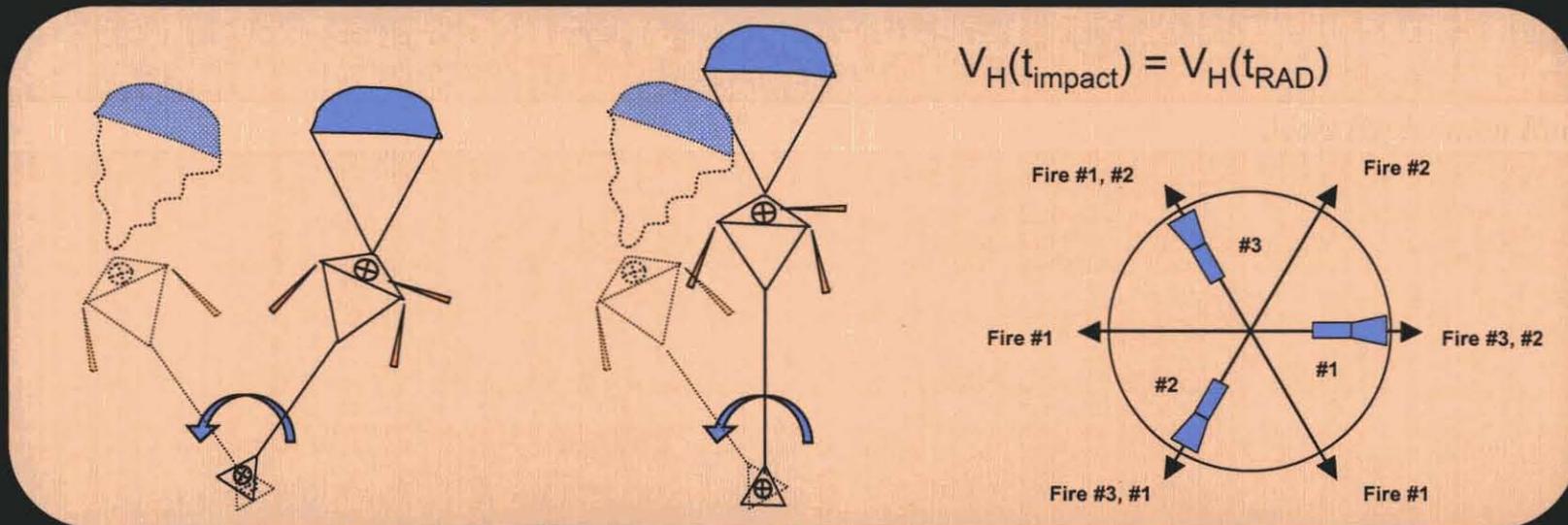


JPL

Mars Exploration Rover

- TIRS - Transverse Impulse Rocket Subsystem

- A very rough backshell “attitude” control system based on backshell attitude as measured by an IMU (inertial measurement unit).
- Works great for canceling the effects of wind shear, but what about steady state winds?





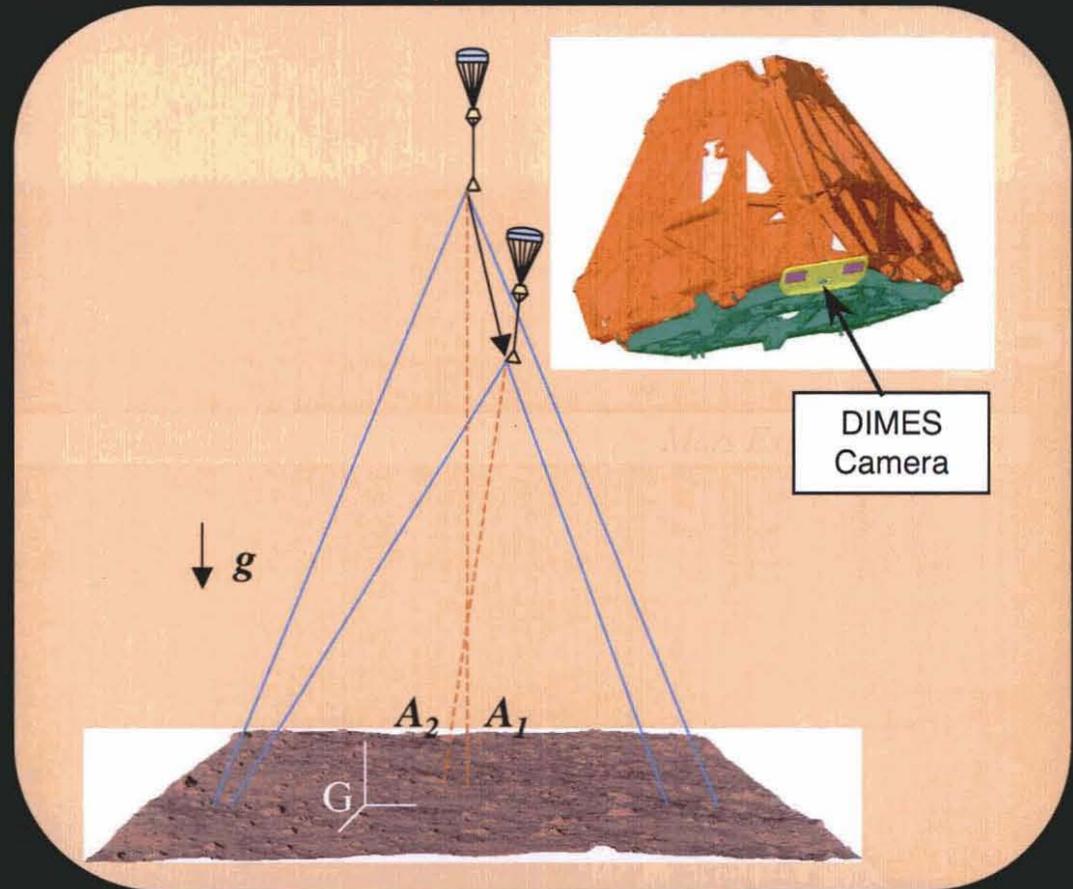
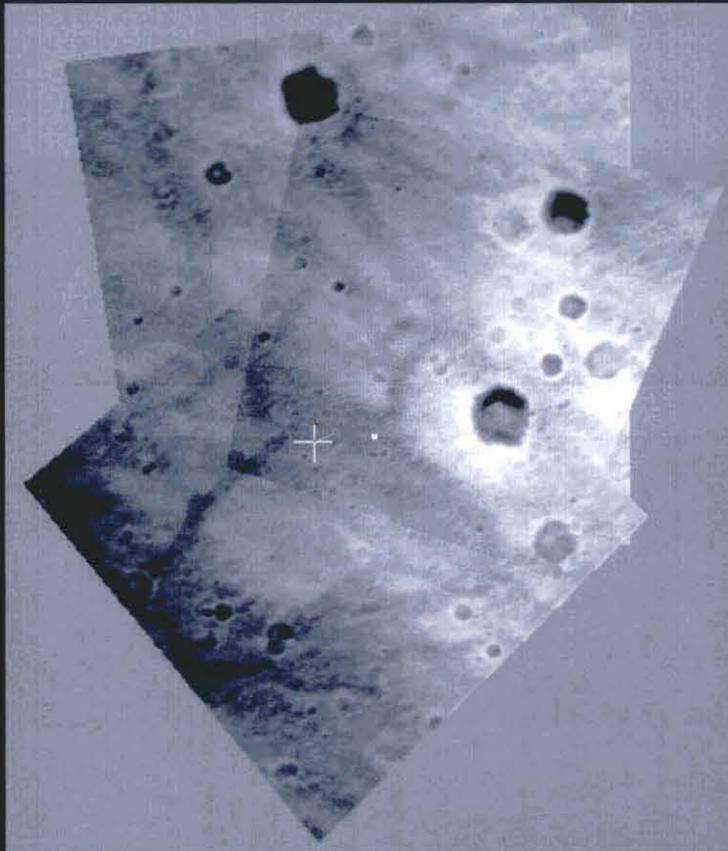
# A Little On-board Image Processing



JPL

Mars Exploration Rover

- DIMES - Descent Image Motion Estimation Subsystem
- Camera plus 2-D image rectification & correlation software
- With “ground-truth” velocity on-board software could pick the best TIRS rocket combination that would null the total velocity.





# EDL Preparations



JPL

*Mars Exploration Rover*

- Team spent six months testing and improving on the EDL flight software before it was loaded in Dec.
  - There were at least 2 landings every night, 7 days a week for 4 months using our flight-like testbed at JPL.
- The project practiced EDL operations (including the Cruise, Navigation and EDL teams and the Deep Space Network) many times before landing.
  - Every detail was simulated, right down to the 12 min one-way light time delay to the DSN.
- A “failure” review “Red team” had been formed prior to landing.
  - With only 3 weeks between landings there was no time to round up a failure review board.
  - In the hours and days following Spirit’s landing, the Red team would follow and critique the action as the EDL team reconstructed the landing and made recommendations on risk reduction for Opportunity’s landing.
  - The Red team participated in the project’s operations readiness tests in November ‘03.



# End of one Road and the Start of a New



**JPL**

*Mars Exploration Rover*

- Spirit Landed at 8:25:36 pm PST on Jan 3, 2004.
  - Confirmation of a safe landing 18 min later.
- Opportunity landed at 8:54:22 pm PST on Jan 25, 2004

