

# Red Rover, Red Rover: Landing Rovers on Mars

Dr. Daniel P. Scharf  
Guidance & Control Analysis Group  
Jet Propulsion Laboratory  
California Institute of Technology

University of Iowa  
Department of Mechanical & Industrial Engineering  
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## Overview

- Introduction
  - Overview of Jet Propulsion Laboratory
- Why go to Mars
- Mars Exploration Rover (MER)
  - Overview
  - Entry, Descent & Landing
  - Landing Data from Mars
- Mars Science Laboratory (MSL)
  - Overview
  - Skycrane Descent & Landing Concept
- Working at JPL
- MER Pictures

## Introduction

- The mission of the Jet Propulsion Laboratory (JPL) is the robotic exploration of the solar system
  - Owned and managed by the California Institute of Technology (Caltech)
  - Under contract to NASA
- Located in the foothills of the San Gabriel Mtns. in Pasadena, CA
- Employs ~4900 staff and ~600 contractors



## JPL

- Why is it called the "Jet" Propulsion Laboratory?
  - The Caltech group that would eventually become JPL designed the first jet-assisted take-off (JATO) rockets for the US Army Air Corps, circa 1940.
- At the time, "rockets" were considered science fiction, the domain of Flash Gordon and Buck Rogers
  - "Jet" was politically correct

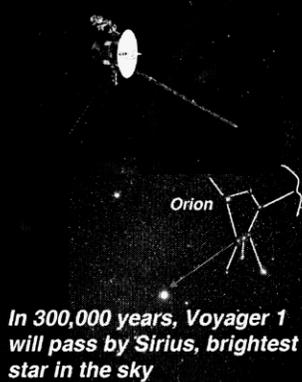


First U.S. Jet Assisted Take Off  
March Field, California on August 12, 1941

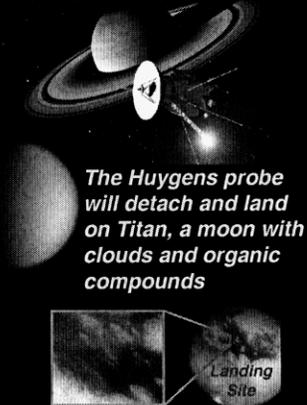
## JPL Missions Today

- JPL is involved in 20 missions in orbit about the Sun, Earth, Mars, and beyond. A sampling...

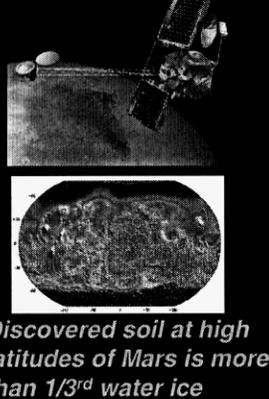
Voyagers 1 and 2



Cassini



Mars Odyssey



## Mars Rovers

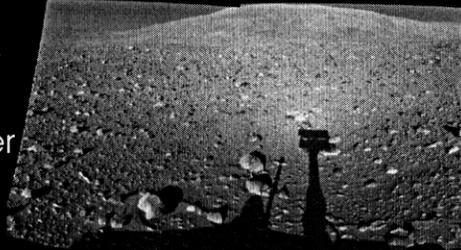
- NASA Vision:
  - To improve life here,*
  - To extend life to there,*
  - To find life beyond.*
- Liquid water is necessary for life (as we know it)
  - **"Follow the water!"**
- Rover missions conceived to be robotic geologists
  - Confirm or refute liquid water in Mars past
- Rover Missions
  - Mars Pathfinder - 1996
  - Mars Exploration Rovers (MER) - 2003
  - Mars Science Laboratory (MSL) - 2009



## MER Overview

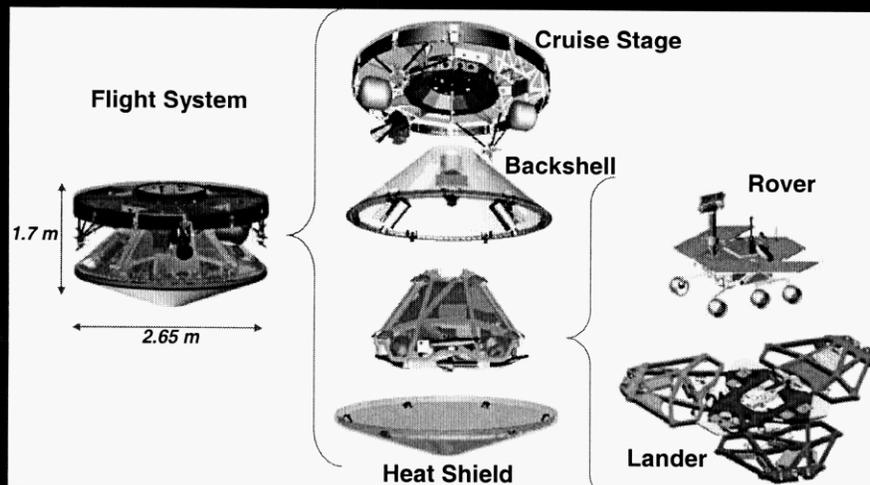
- Two solar-powered rovers, Spirit and Opportunity
  - Each can travel ~40 m a day
- Robotic arm with three instruments and an abrader
- Stereoscopic camera with "eyes" at human height
- Opportunity found conclusive evidence of liquid water in Mars' past
- Both still running strong, 200 "sols" past warranty

*Spirit's shadow below Columbia Hills*



*Outcrop on Meridiani Planum where Opportunity discovered evidence of liquid water*

## MER Spacecraft

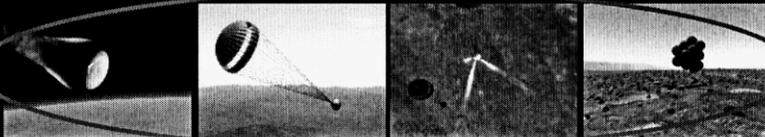


## Three Rover Mission Phases

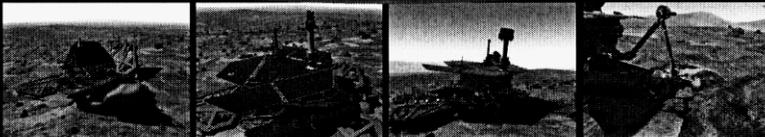
Launch  
& Cruise



Entry,  
Descent &  
Landing  
(EDL)

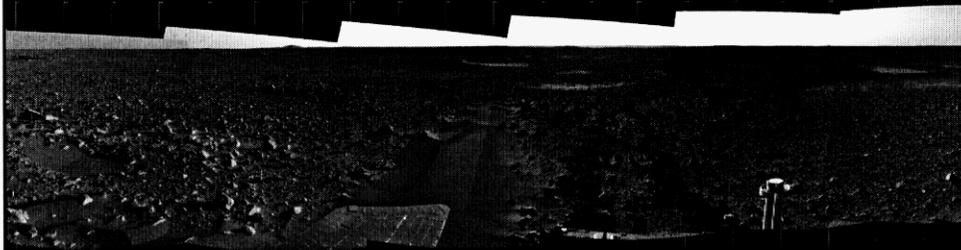
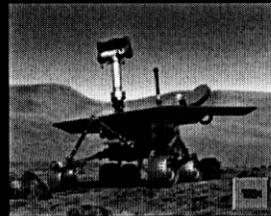


Egress &  
Surface  
Operations



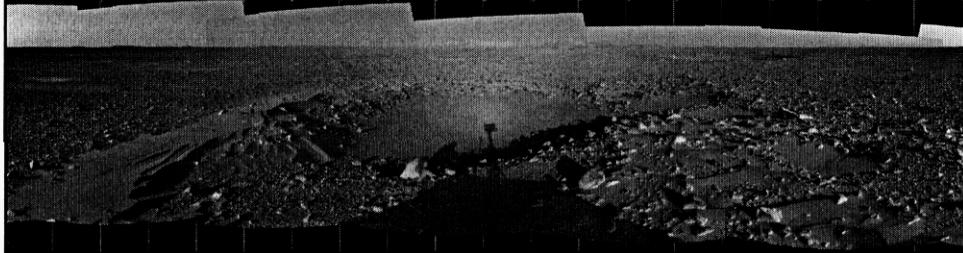
## MER Mission Animation

- Animation of MER mission
  - Launch
  - Mars Transfer Orbit Injection
  - Abbreviated Cruise
  - Entry, Descent and Landing (EDL)
  - Rover Egress
  - Surface Operations/Example science
- Mars looks like a hot desert, but highs just reach freezing and lows can be  $-150^{\circ}\text{F}$

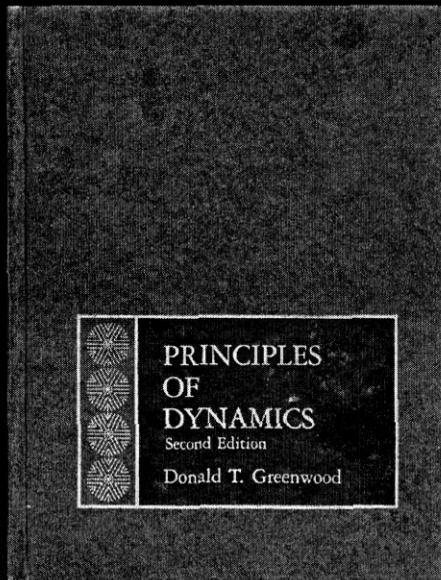


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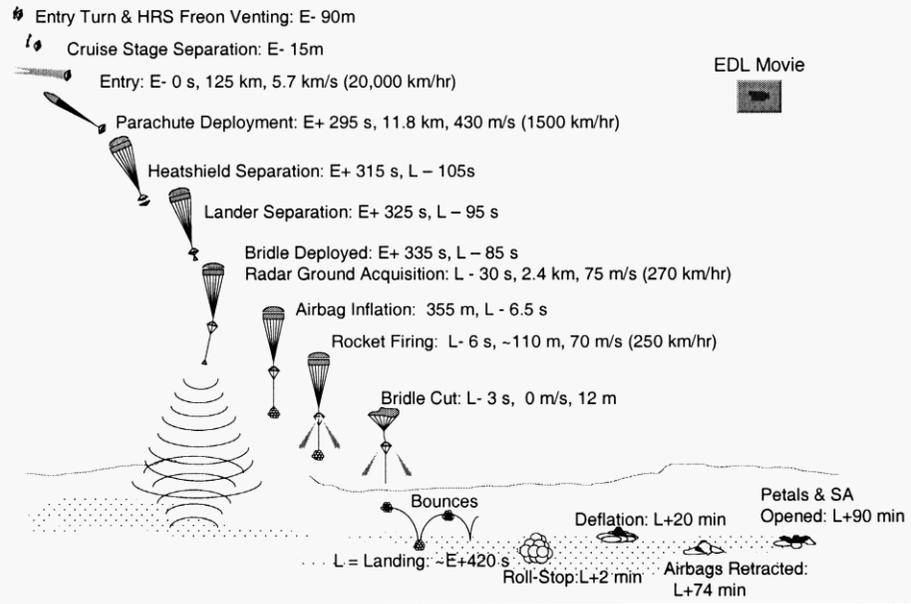


## And I'm Learning this Because?



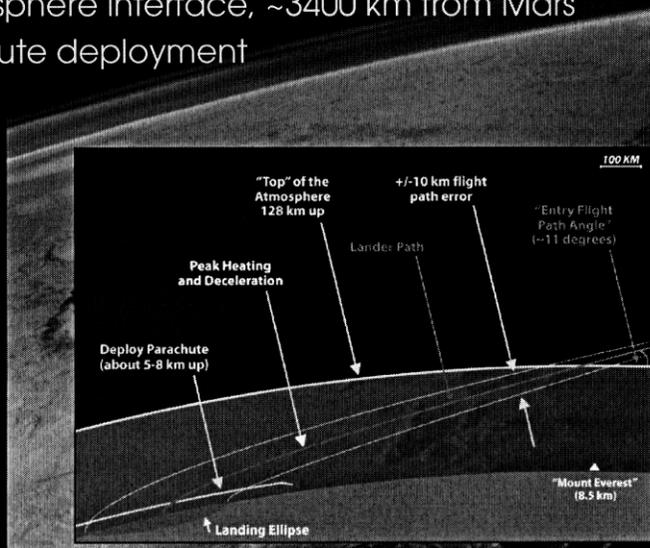
- *From homework to Mars!* Intermediate Dynamics
  - First year grad course
- Culminates in dynamics of rigid bodies
  - Spacecraft ~ rigid body
  - Stability of spinning bodies
  - Attitude Representations
    - Euler Angles
    - Rotation Matrices
    - Quaternions

# Entry, Descent & Landing Timeline



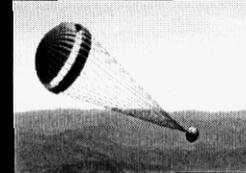
# MER Entry

- Need to enter atmosphere at  $11^\circ$  else will burn up or skip
- Begins at atmosphere interface, ~3400 km from Mars
- Ends at parachute deployment



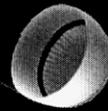
## MER Descent

- Parachute deploy based on accelerometer reading
  - Pop chute a set time after peak accel



- MER based on Pathfinder
  - But MER twice as heavy!

- Parachute design is an art
  - Early test 
  - Near-final test 

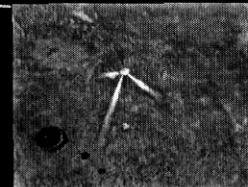


- Retro-rockets fire

110 m, 190 mph, L -6 s

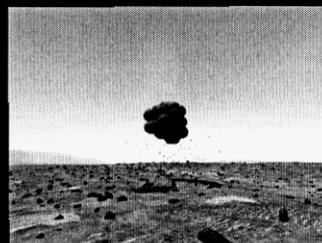


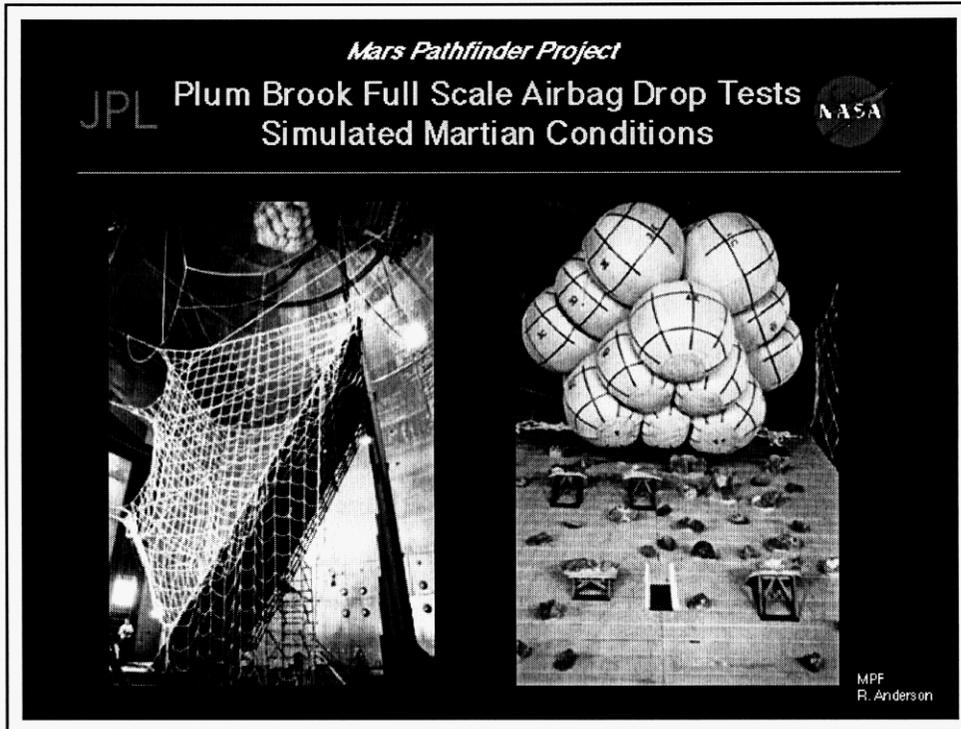
12 m, 0 mph, L -3 s



## MER Landing

- MER landing system based on Pathfinder system
  - Three story drop onto airbags
- Why three stories?
  - Accuracy of inertial navigation system (~5 m)
  - Margin
- MER heavier by ~20%
  - Need to retest airbags
- Pathfinder airbag design not sufficient
- Test new designs at Plum Brook
  - Initial test 
  - Exploratory test 
  - Near-final test 





## MER Landing Data - Inertial Navigation

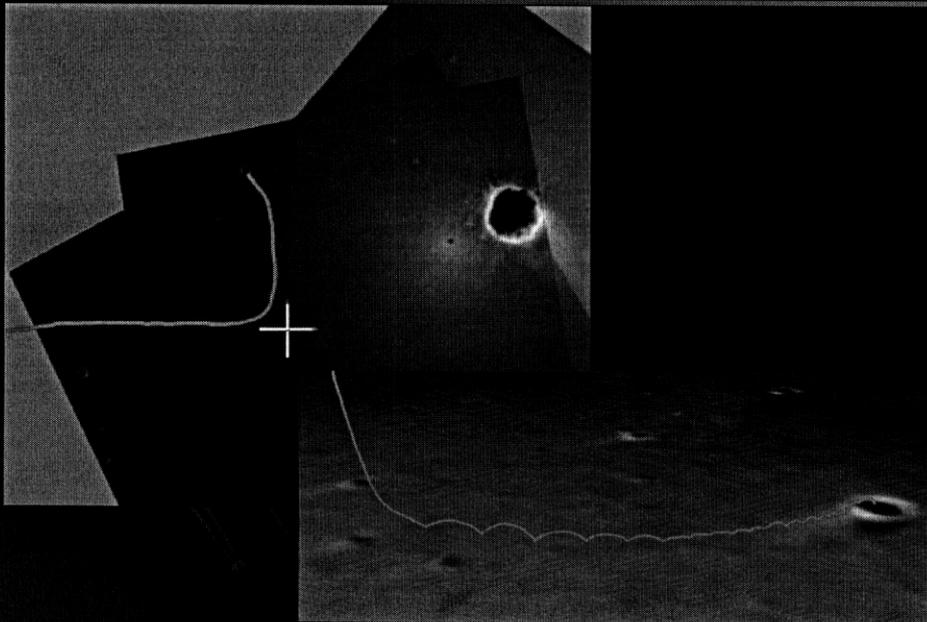
- Spacecraft lands autonomously
  - Roundtrip light-time was 20 minutes
  - EDL takes 6 minutes
- How does lander know where it is?
  - Inertial Navigation
  - Radar altimetry
- Inertial Navigation
  - Position
    - Measure translational acceleration with accelerometer
    - Add in gravity
    - Integrate twice
  - Attitude
    - Measure rotational velocity with gyroscopes
    - Integrate once (to get quaternion!)

## Spirit Landing Reconstruction (from Mars)

- Telemetry from landing radioed back to Earth
- Engineer simulations used to visualize telemetry
- Descent
  - Inertial Navigation estimates of backshell and lander attitude
  - Inertial Navigation estimates of backshell and lander position and velocity
  - Estimates of chute angle
- Landing
  - Accelerometer records bounces
  - Inertial Navigation estimates of lander position and attitude

- Engineering Simulation
- Animation of Telemetry
- Bounces w/ MGS overlay

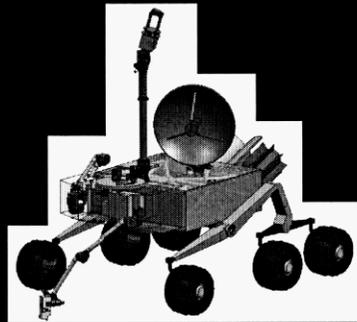
## Opportunity's Hole-in-One



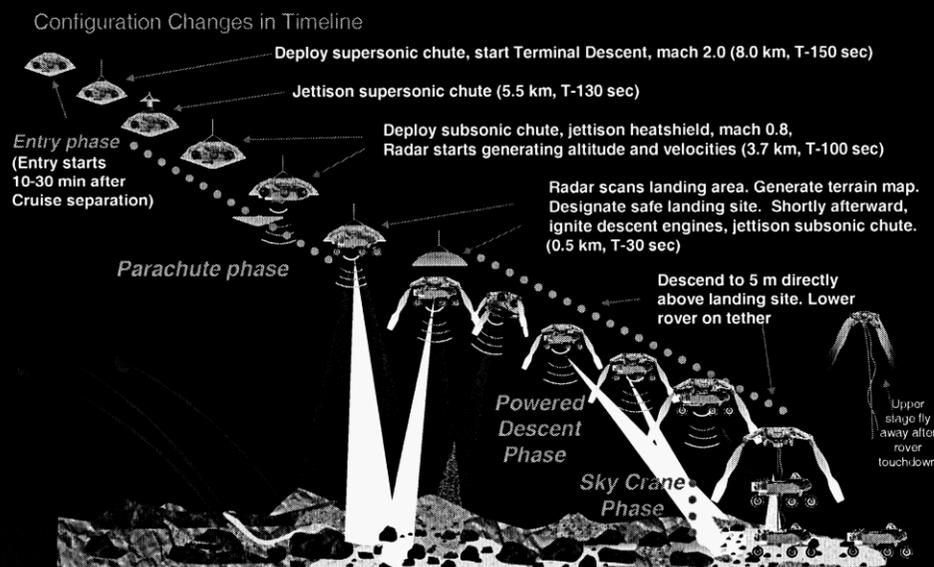
# MSL

- MER and Pathfinder have three main drawbacks
  - Limited lifetime due to decrease in effectiveness of solar panels
  - Limited landing accuracy: landing ellipses ~100x20 km
  - "Straight-in" landers: cannot avoid unsafe slopes, rocks or craters
- Mars Science Laboratory (MSL)
  - A roving science lab, approx. the size of a Mini Cooper
  - Powered by RTGs (nuclear decay) like Voyager and Cassini
- Smart Lander Concept
  - Senses landing area
  - Selects safe landing site
  - Maneuvers lander to new site

all autonomously
- Planned to launch in 2009



## MSL Skycrane EDL Concept



## MSL Simulation

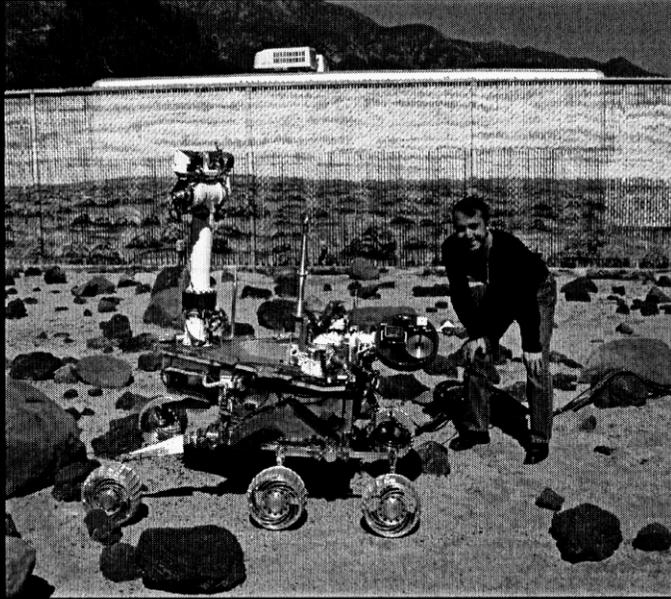
- Powered Descent Phase *engineering* simulation
  - Validate guidance, estimation and control algorithms
  - C-based simulation testbed currently with rigid body models
  - Extensive use of (you guessed it) quaternions



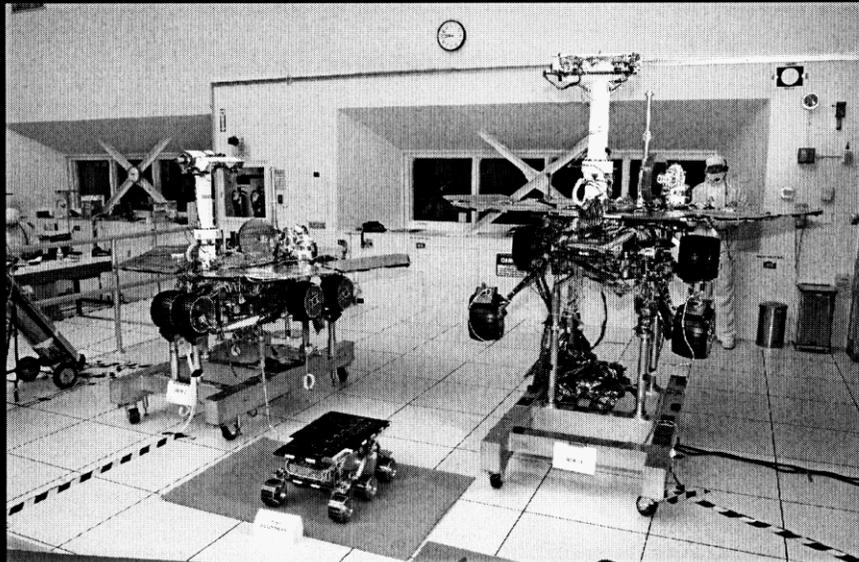
## Practical Constraint

- JPL does world-renowned work
- Guidance & Control Analysis Group
  - 70% PhDs
  - 27% Masters
  - 3 % Bachelors (getting Masters)
- To design
  - A guidance algorithm for landing a rover on Mars
  - An attitude control system for a Europa probe
- You need a graduate degree**
  - Each JPL spacecraft is one-of-a-kind
- Cannot speak for industry, other areas of JPL
  - Mechanical, electrical design
  - Industry route: hands-on more quickly with repeat products

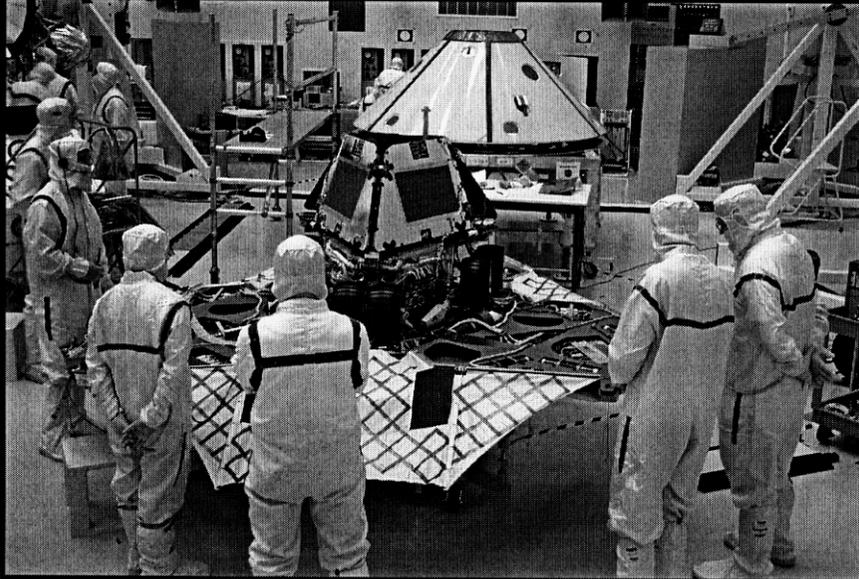
## Me & MER Engineering Model in Mars Yards



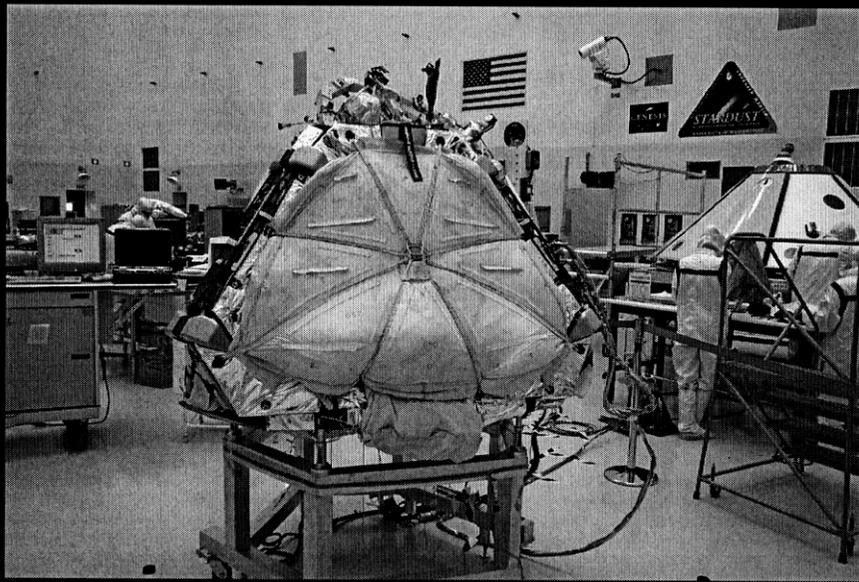
## MER #1, MER #2, & Sojourner Spare Rovers JPL, February 10, 2003



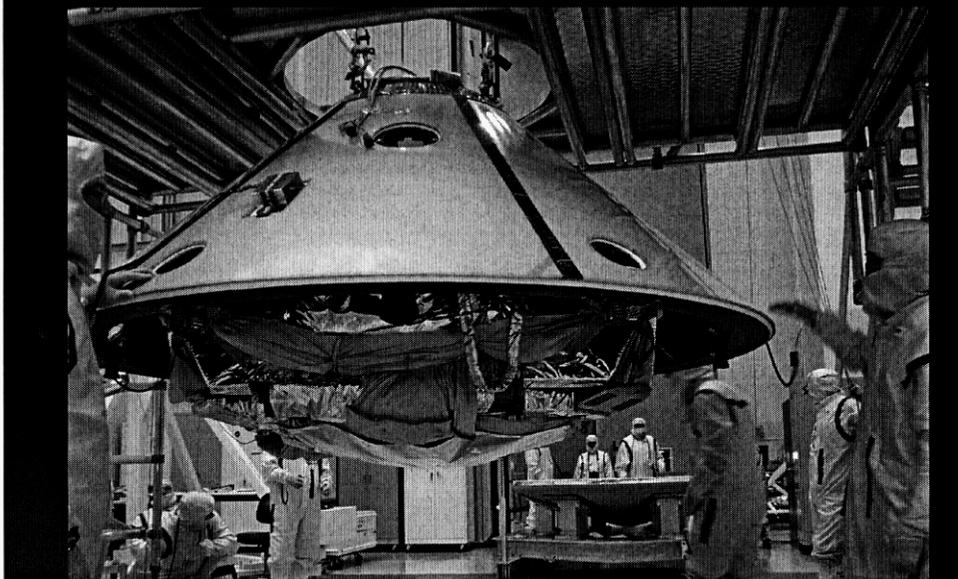
## Stowed Rover and Lander



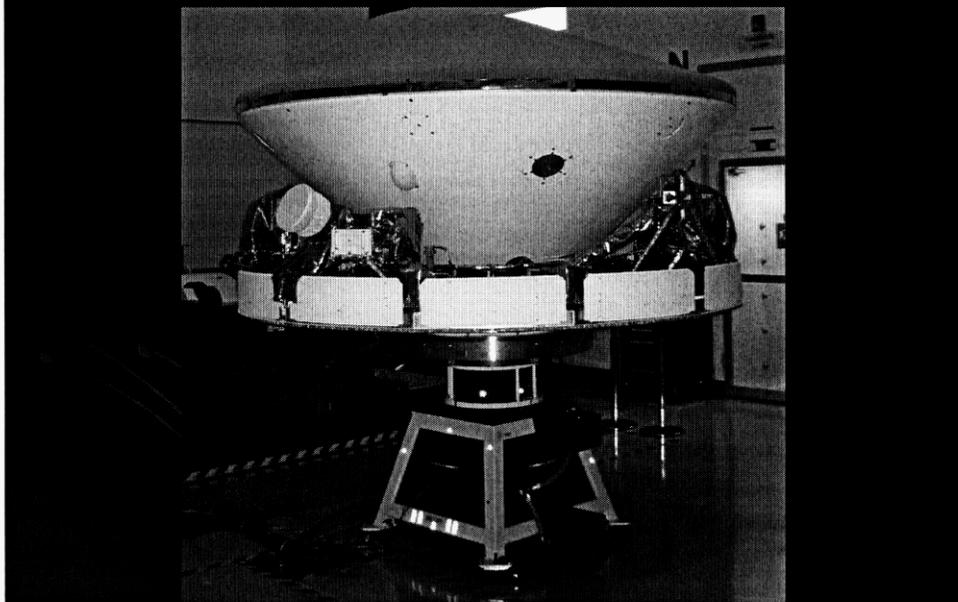
## Integrated Lander



## Lander in Backshell



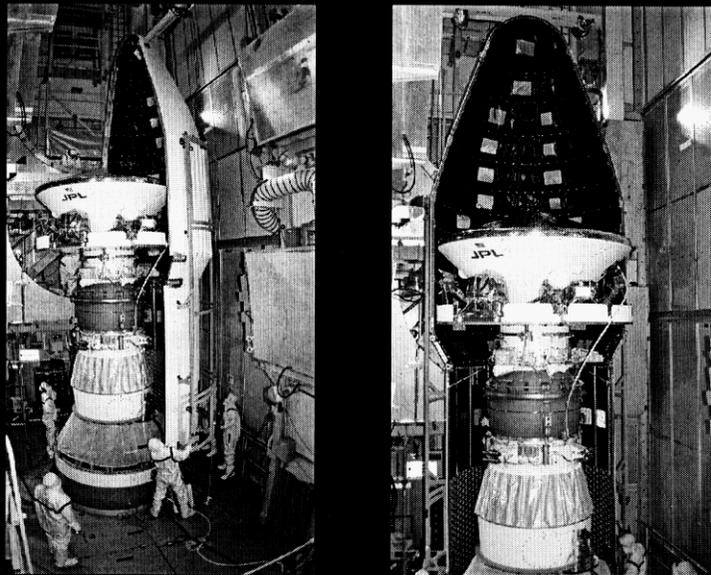
## Launch / Cruise Configuration



## On the Third Stage



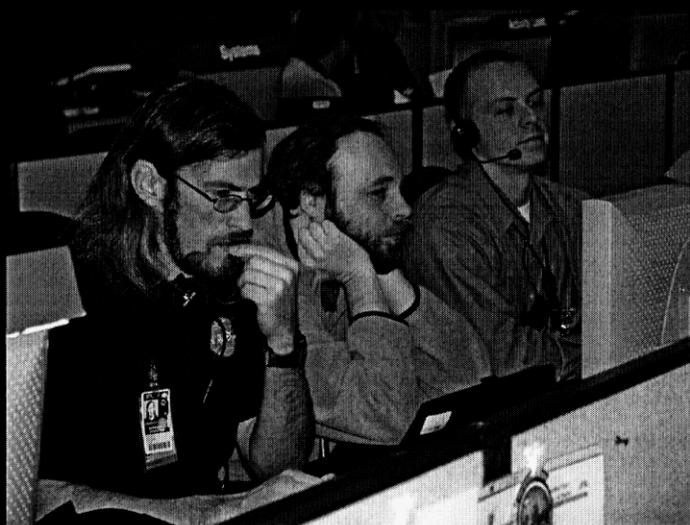
## Spirit in the Fairing



## MER Launch - KSC



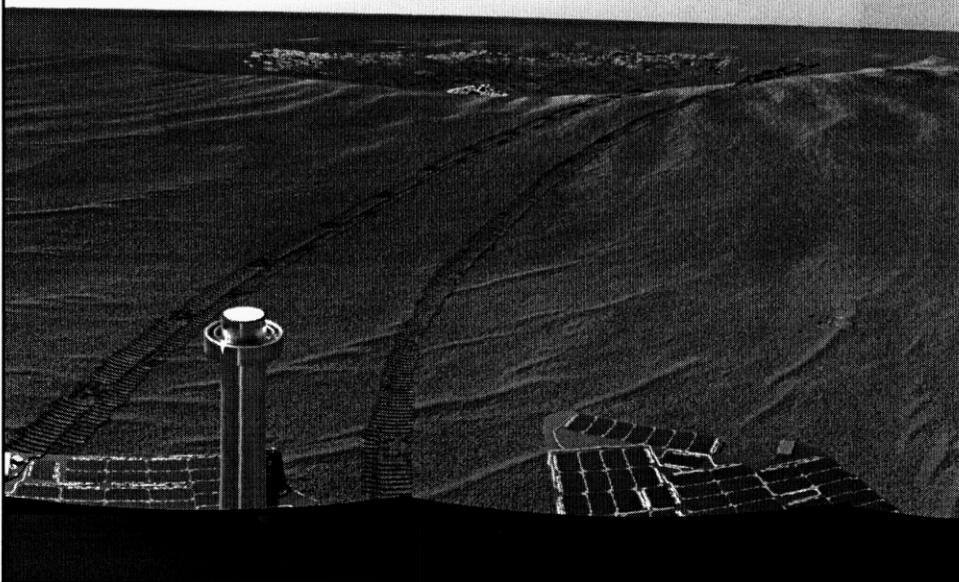
## MER ACS Ops Team Waiting for Signal



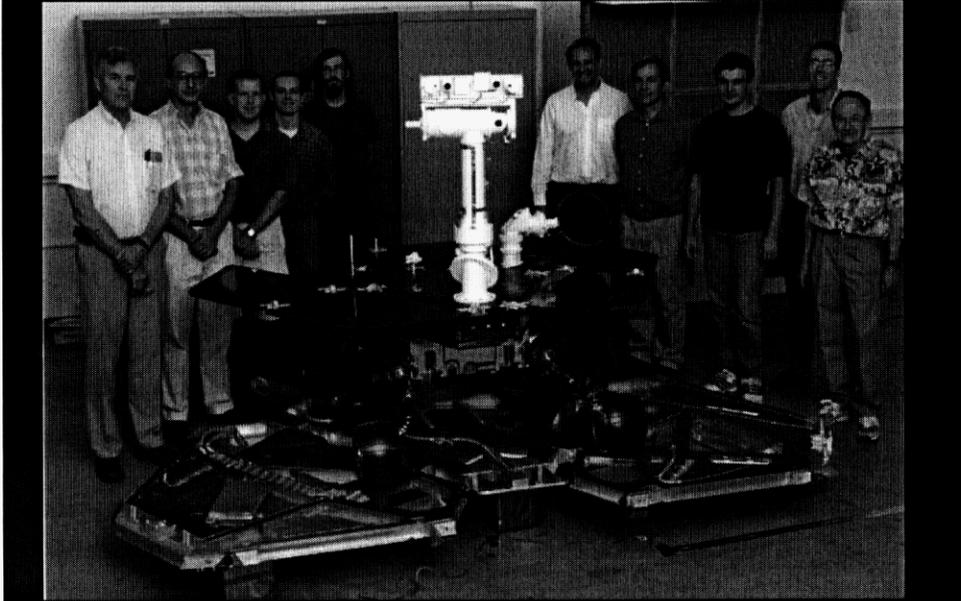
## MER Arnold Visit (1/24/2004)



## Opportunity - Leaves Eagle Crater Sol 57



## Usual Suspects

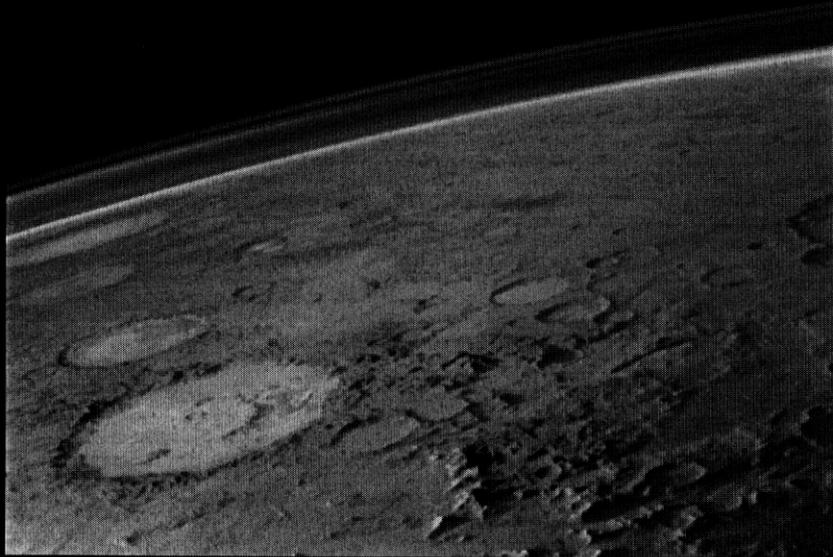


**In 41 attempts by space-faring nations, 26 missions have failed.  
27 orbiters,  
12 landers &  
2 probes.**

**No mission has brought back samples and no one has been to Mars.**

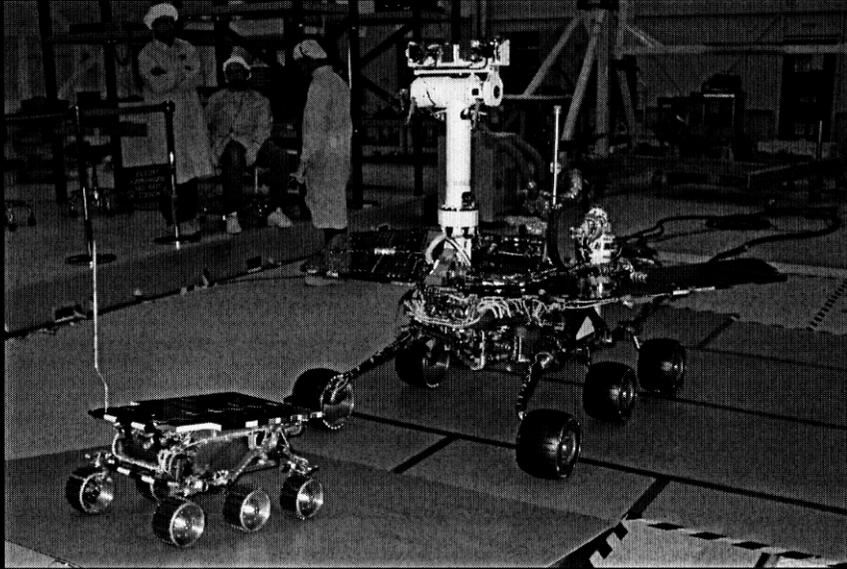
**The End...**

**...But Only the Beginning**



**Supplemental Slides**

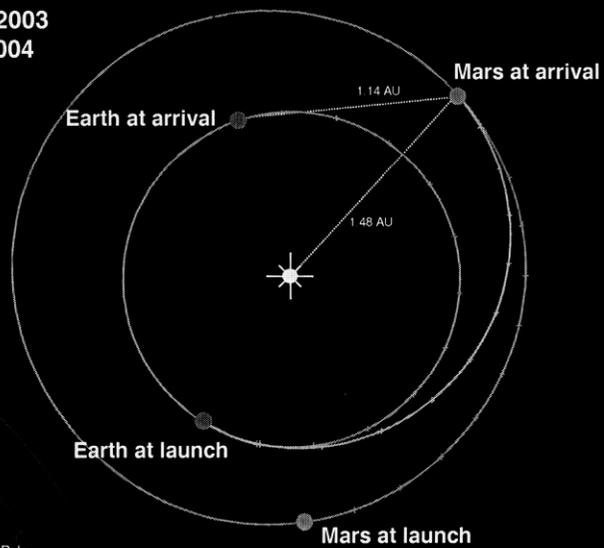
## Old meets new...



## Flying to Mars - it's a *long* trip

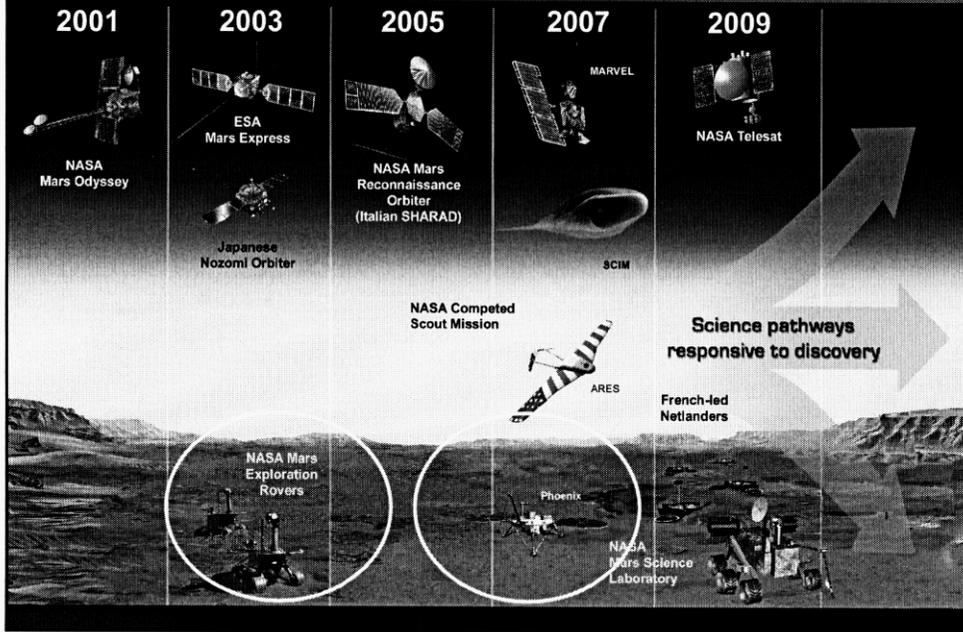
MER-A Open  
Launch 30 May 2003  
Arrival 4 Jan 2004

7 months!

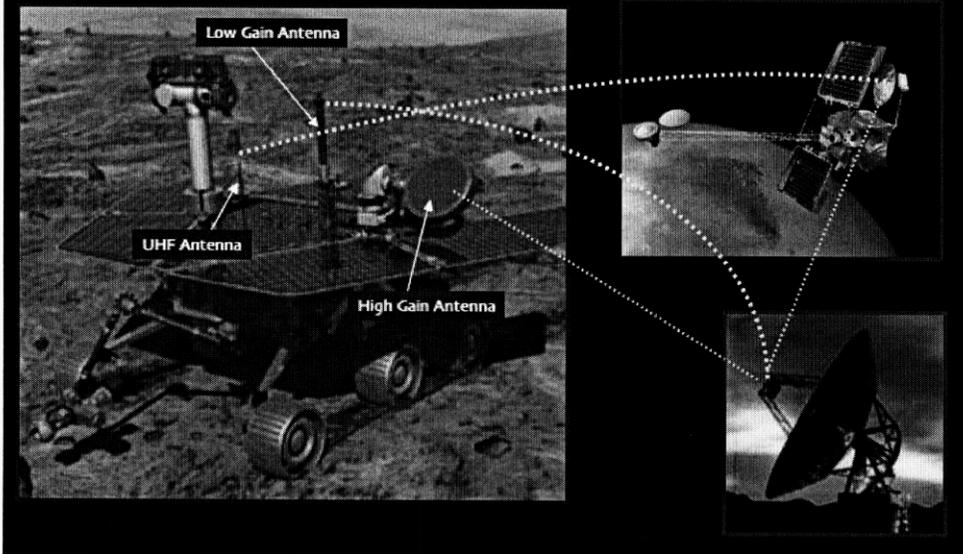


View from Ecliptic North Pole  
20 day tick marks

# Mars Missions: 2001-2009

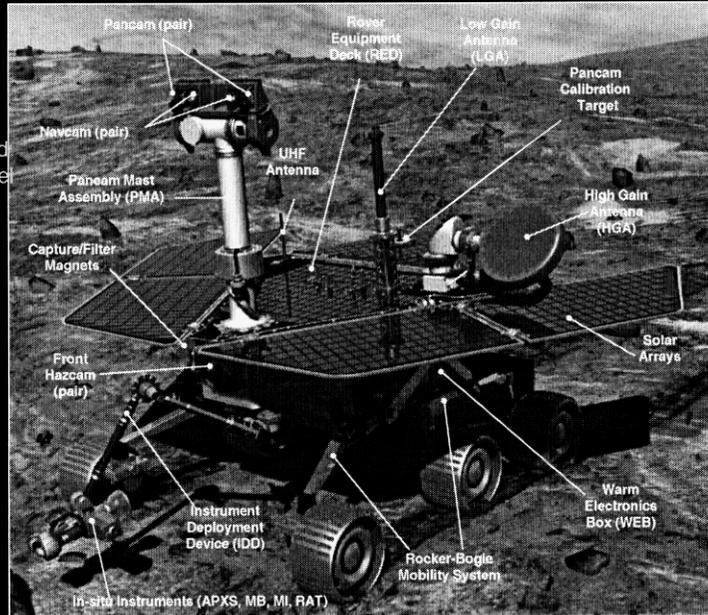


The rovers listen and speak to Earth with their communications antennas.



## Rover Deployed on Mars

- 179 kg
- 1.54 m from ground to Pancam eye level



## My Story

- At 10, a dynamical mind?
  - When passing a truck slowly, can not tell that you are both going over 60 mph
  - Snow falls off a speeding car backwards, but then moves forward when it hits the street
- Watched Voyager flyby of Uranus when I was 12
  - Project Manager was from JPL
- 17 years of school later...
  - Univ. of Minnesota BS Aerospace
  - Univ. of Michigan MS & PhD Aerospace
  - **Intern** at JPL
- Now at JPL working on formation flying

# Mars — a bitter history

(stats as of 2002)



	usa	ussr/russia	japan	esa	successful	failures
orbiters/flyby	12	-	-	-	8	4 (2 LV)
	-	15	-	-	4	11 (5 LV)
	-	-	1(*)	-	(?)	(?)
	-	-	-	-	-	0
landers	6	-	-	-	3	3
	-	8	-	-	0**	8 (2 LV)
	-	-	0	-	-	-
	-	-	-	-	-	-
totals	18	23	1	0	15	26
					37%	63%

\* Japan's Nozomi still en route after inflight anomaly in 1998 forced it to go the long-way round. She's down but not yet out.

\*\* Mars 3 in 1971 apparently transmitted for 20 sec after landing but no significant information was returned

Spirit, 03/7/04



## Spirit's Sky Observations

Spirit snapped a picture of Earth from Mars and watched the sky at night with its panoramic camera.

You are here



Spirit, 03/11/04



## Spirit's Sky Observations

Spirit imaged the stars in the upper part of the constellation Orion, including the bright shoulder star Betelgeuse and Orion's three-star belt.



Spirit, 03/11/04



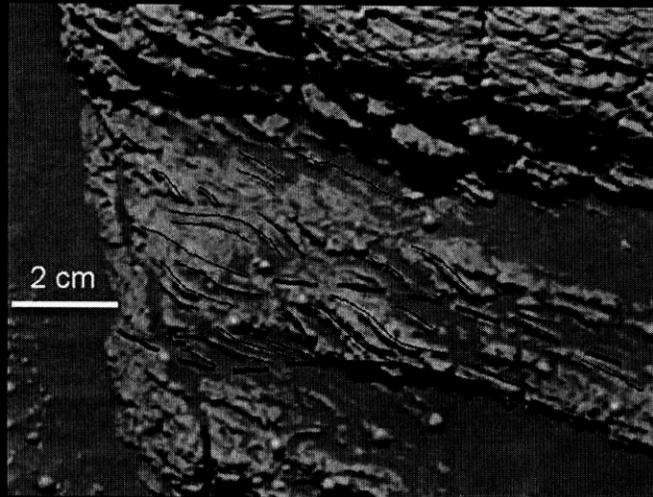
## Spirit's Sky Observations

It's a Bird,  
It's a Plane,  
It's a...  
Spacecraft?

Observing the sky with a green filter, Spirit came across a surprise streak!

The leading theory is that the Unidentified Flying Object is the inactive Viking 2 orbiter sent to Mars in the 1970's.





*Panoramic camera image of Last Chance*

The dips of fine layers at angles to each other are telltale signs that water flowed from left to right in this rock.

## Goodbye To Eagle Crater

