Jet Propulsion Laboratory
California Institute of Technology

Planetary Robotic Exploration
Mobility and Autonomy

Issa A.D. Nesnas
Supervisor, Robotic Mobility Group
Robotics and Mobility Systems Section
Jet Propulsion Laboratory

Public Presentation
University of Colorado Boulder
Engineering Center
April 24, 2013

Why Planetary Mobility?

Jet Propulsion Laboratory
California Institute of Technology

- Enables precise *in situ measurements* on disparate targets
- Provides greater *flexibility* for targeted investigations (e.g. sampling)
- Enables *opportunistic* investigations of new discoveries
- Enables site *characterization*

Limitations

- Limited surface coverage compared to orbital assets but greater coverage compared to fixed landers
- More complex and more expense

Jet Propulsion Laboratory
California Institute of Technology

Why Autonomy?

- Mitigates communication delays and limited communication windows. E.g. for Mars*:
  - Round-trip delays range from 8-42 minutes
  - Logistics of Deep Space Network limit uplinks typically to one/day
- Greater operational capability despite limited communication bandwidth

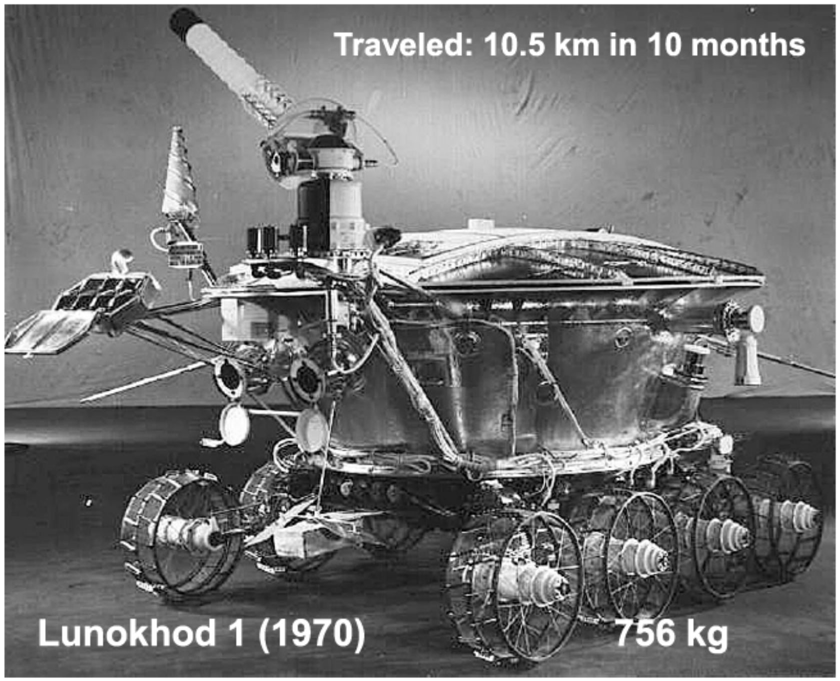
Challenges

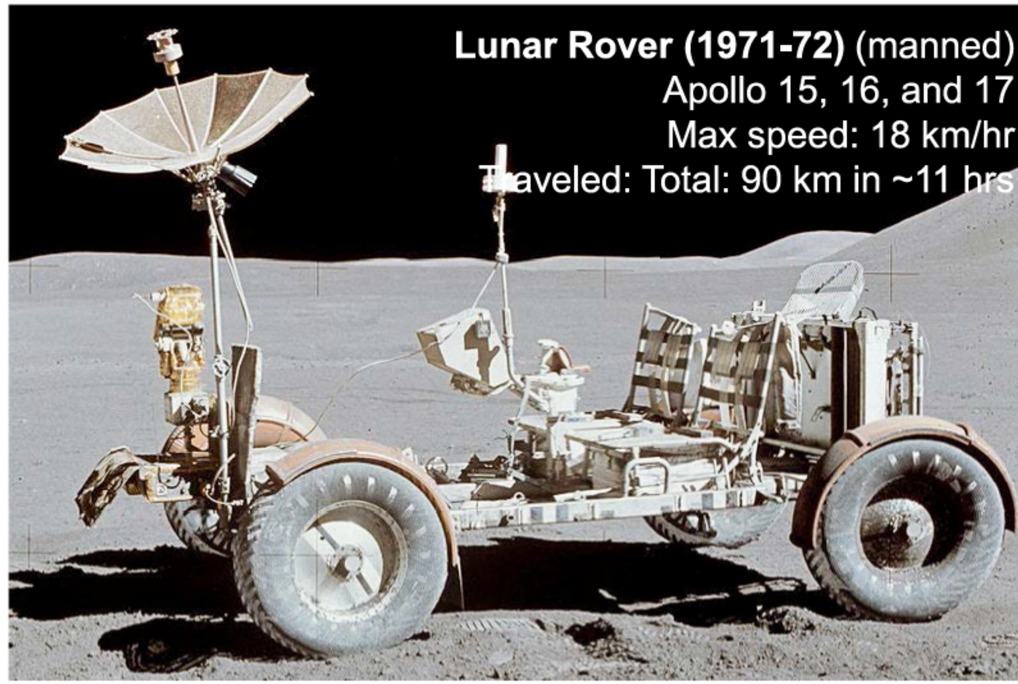
- Reasoning about large uncertainties
- Limited computational resources
- Radiation-hardened avionics
- Limited power, hence agility and dexterity

** Reference: M. Maimone – AIAA 2009, “From Sojourner to MSL”*

First Planetary Rovers Destination: *the Moon*

Lunokhod 1A (1969)
Failed on launch





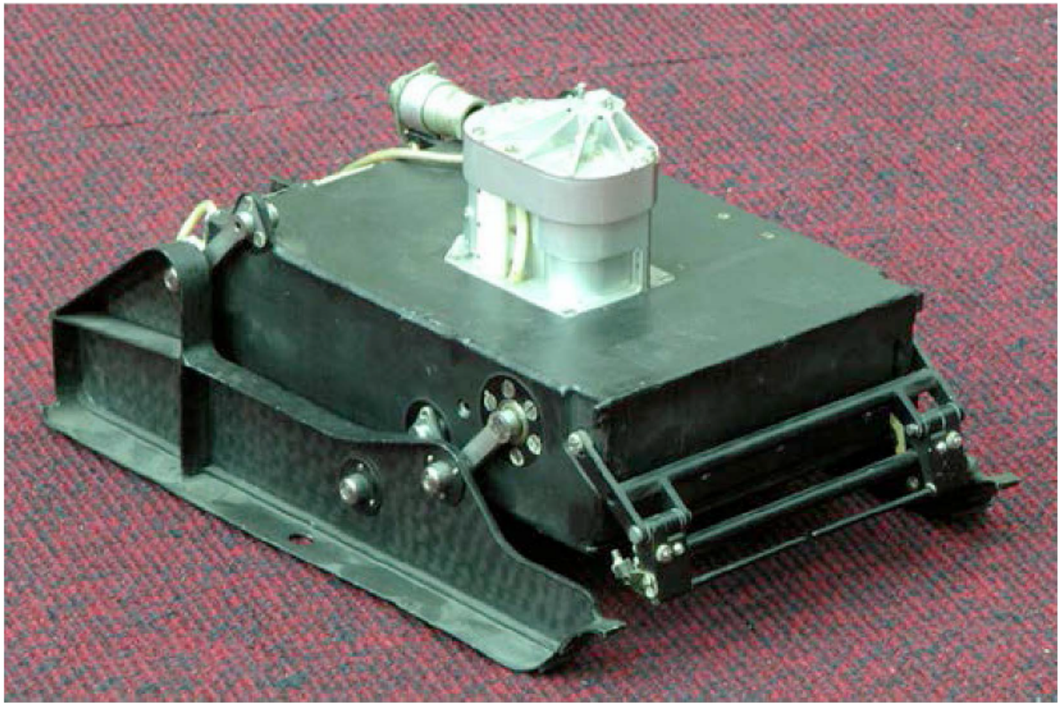
Lunokhod 2 (1973)
Traveled ~37 km in ~4 months, including hilly areas and rilles

Early Rovers

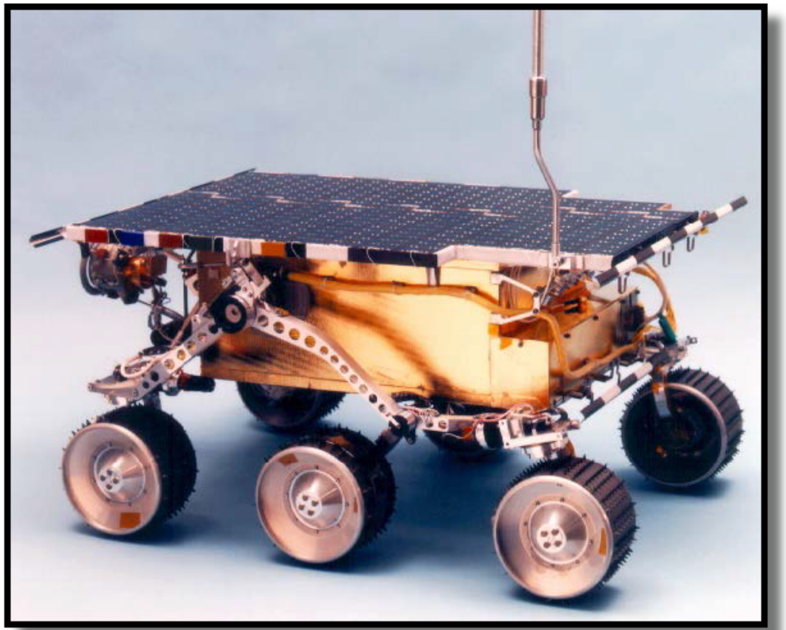
In the early 1970s, a 4.5 kg Mars rover was on board the Soviet Mars 2 and Mars 3 landers.

Tethered to the lander with a 15 m umbilical and deployed using a robotic arm, these rovers would have moved across the surface on skis. They had mechanical bumpers for autonomous obstacle avoidance

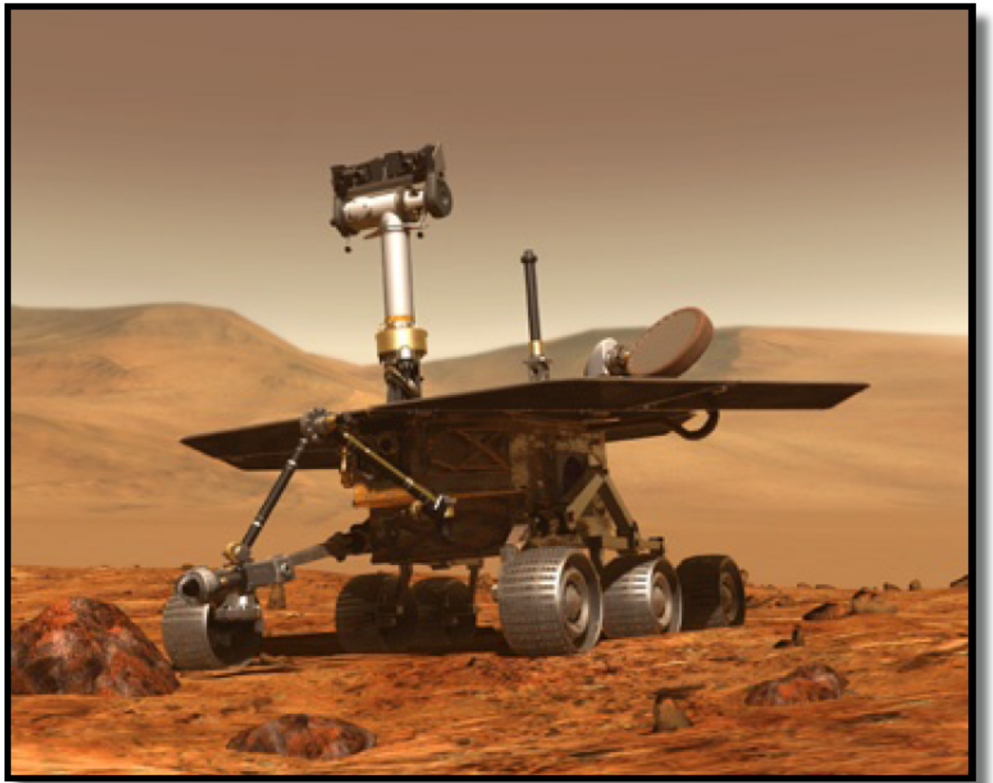
Unfortunately, the rovers were never deployed as the Mars 2 and Mars 3 landers failed.



Recent Rovers Destination: *Mars*



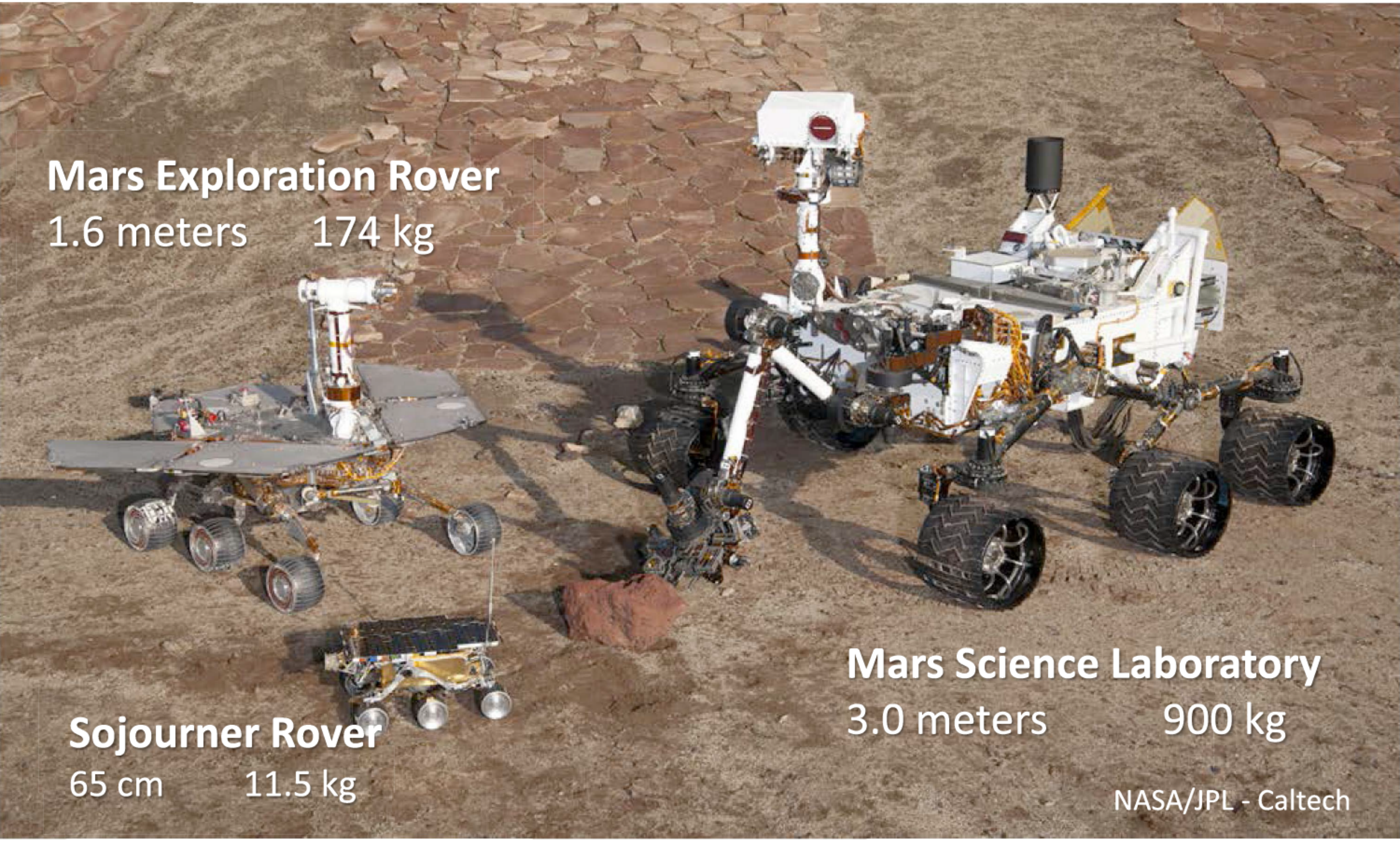
Sojourner (1997)



Spirit (2004)
Opportunity (2004)

Jet Propulsion Laboratory
California Institute of Technology

More Recent Robots Destination: *Mars*



RESEARCH AND FLIGHT

MOBILITY FORMS

Different Forms of Mobility

Aerial

Titan **aerobots and**
Venus **balloons**

Jet Propulsion Laboratory
California Institute of Technology

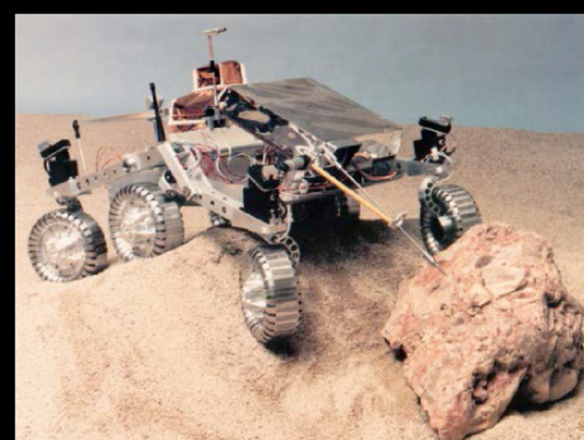
Different Forms of Mobility

Wheeled

SLRV (1964) (JPL and GM)

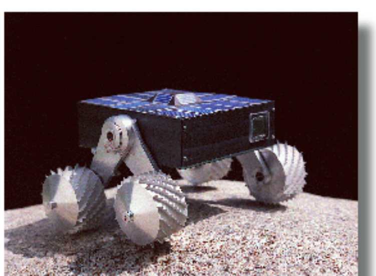
Blue Rover (1986)

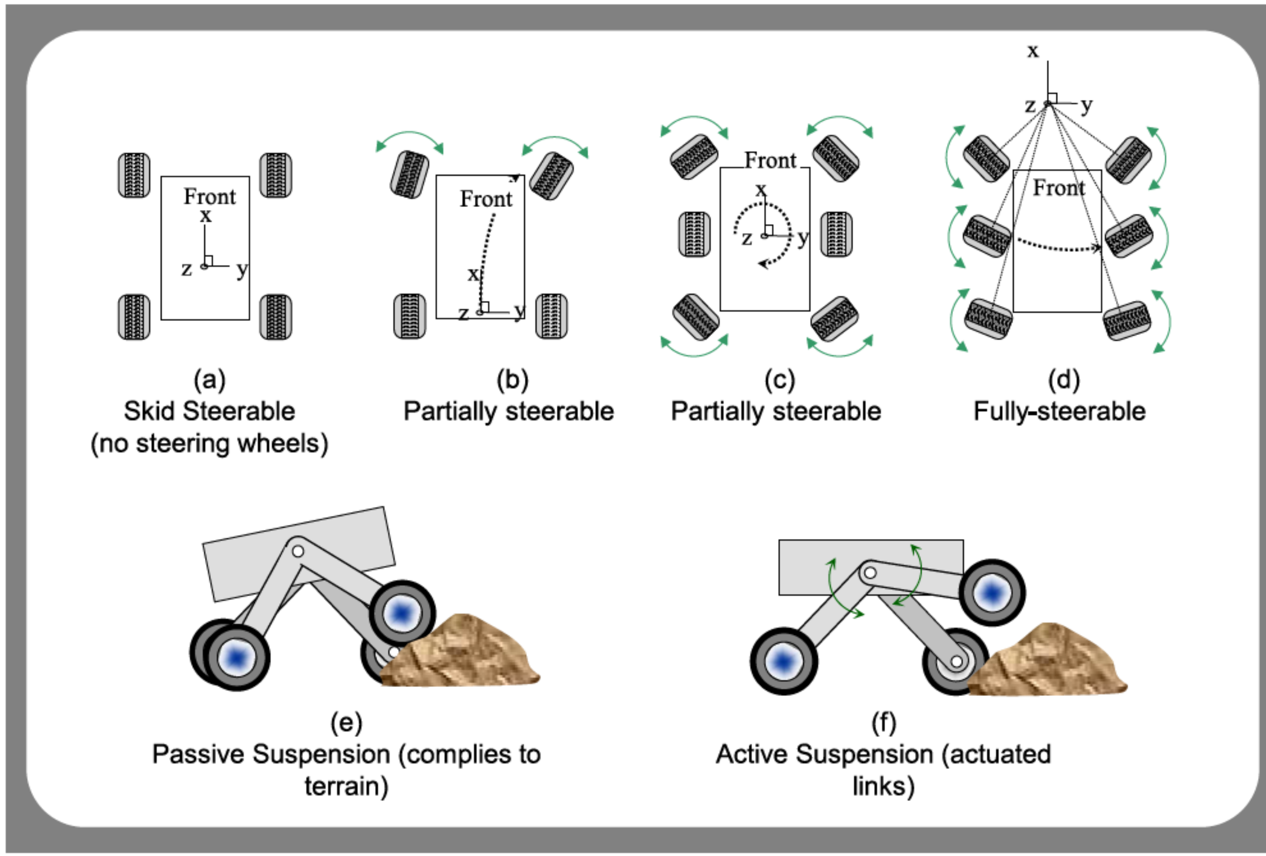
Robby (1990)



Rocky 4 (1992)

Maneuvering





Different Forms of Mobility

Legged / Hybrids

LEMUR (2005) B. Kennedy (PI)

ATHLETE Field Test
Meteor Crater, AZ
September 3-15, 2006

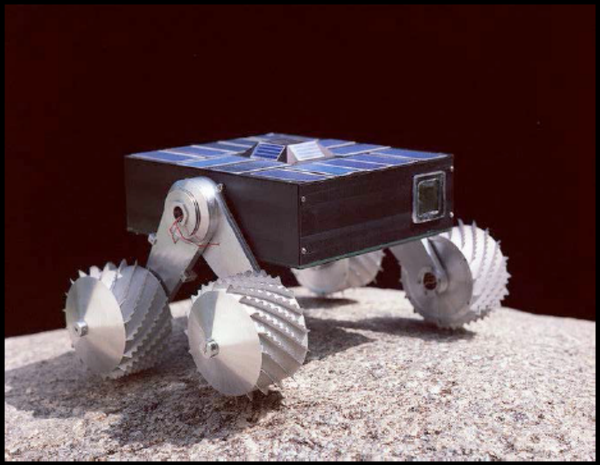
(video sped up)

ATHLETE (2005) B. Wilcox (PI)

Different Forms of Mobility

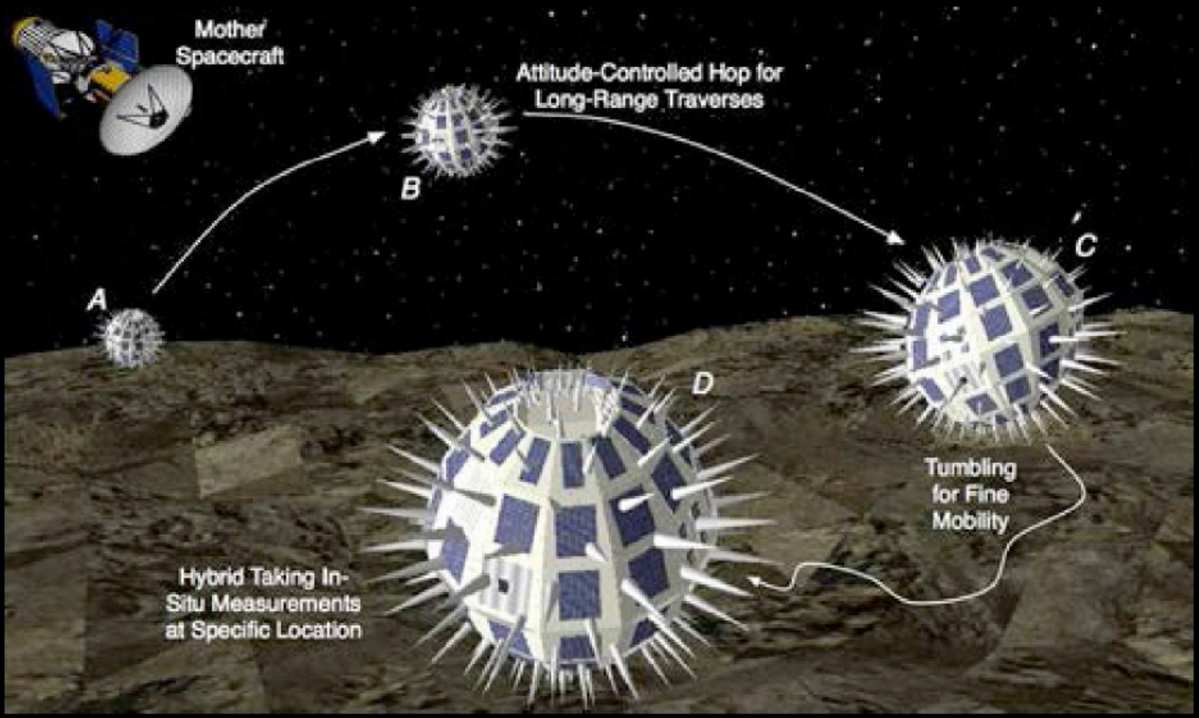
Hybrid Hoppers

Microgravity



Nanrover (1997) B. Wilcox (PI)

Asteroid nanorover
NEO hybrid

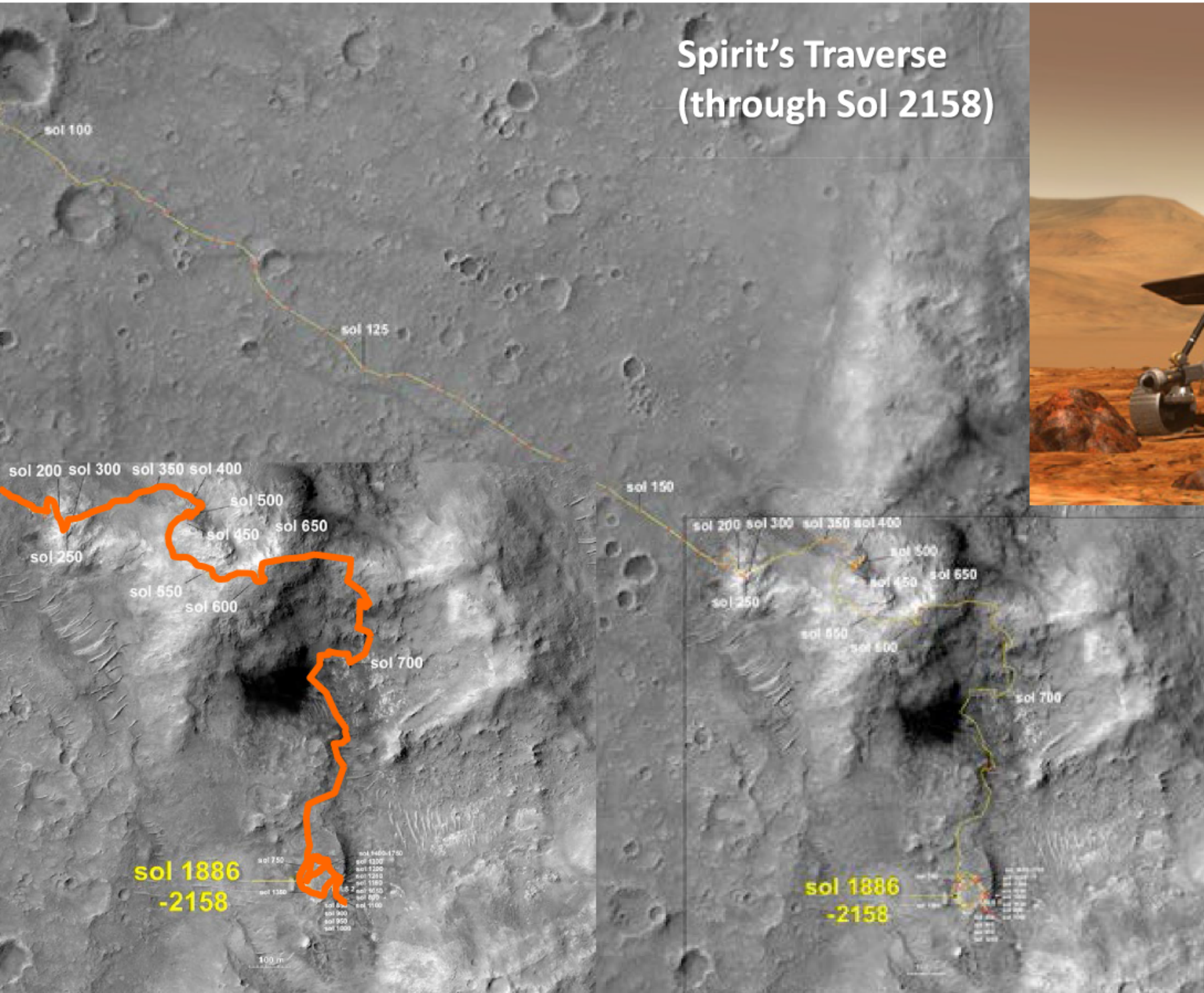


JPL/Stanford/MIT (Pavone, Nesnas, Castillo-Rogez, Hoffman)

RESEARCH AND FLIGHT

ON-BOARD AUTONOMY

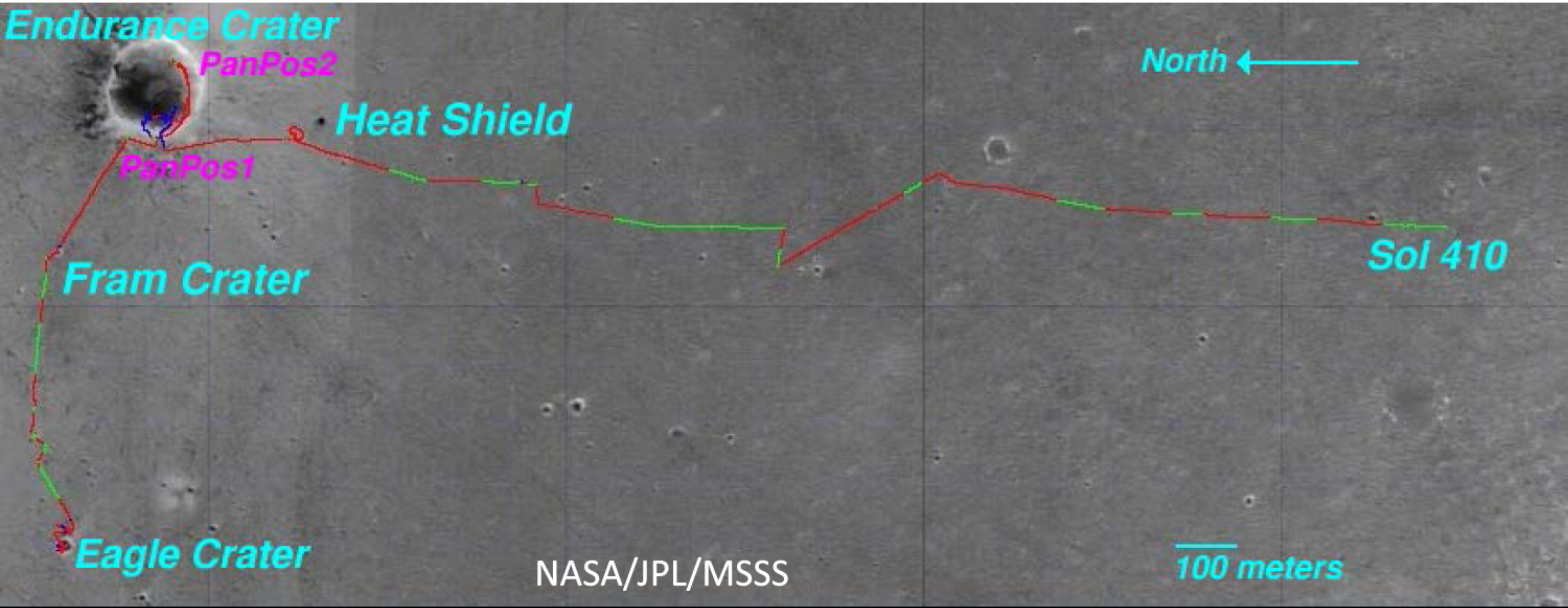
Mars Exploration Rovers Traverses



- Spirit traversed: 7.7 km
- To date Opportunity traversed: 35.65 km

Opportunity Traverse (through Sol 410)

Jet Propulsion Laboratory
California Institute of Technology

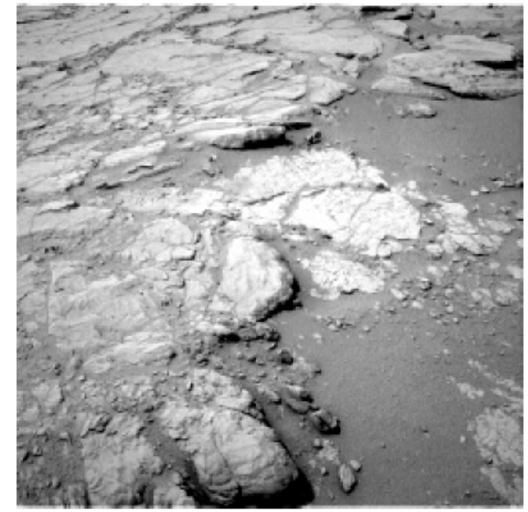


Adapted from a Slide by M. Maimone

Driving Modes:

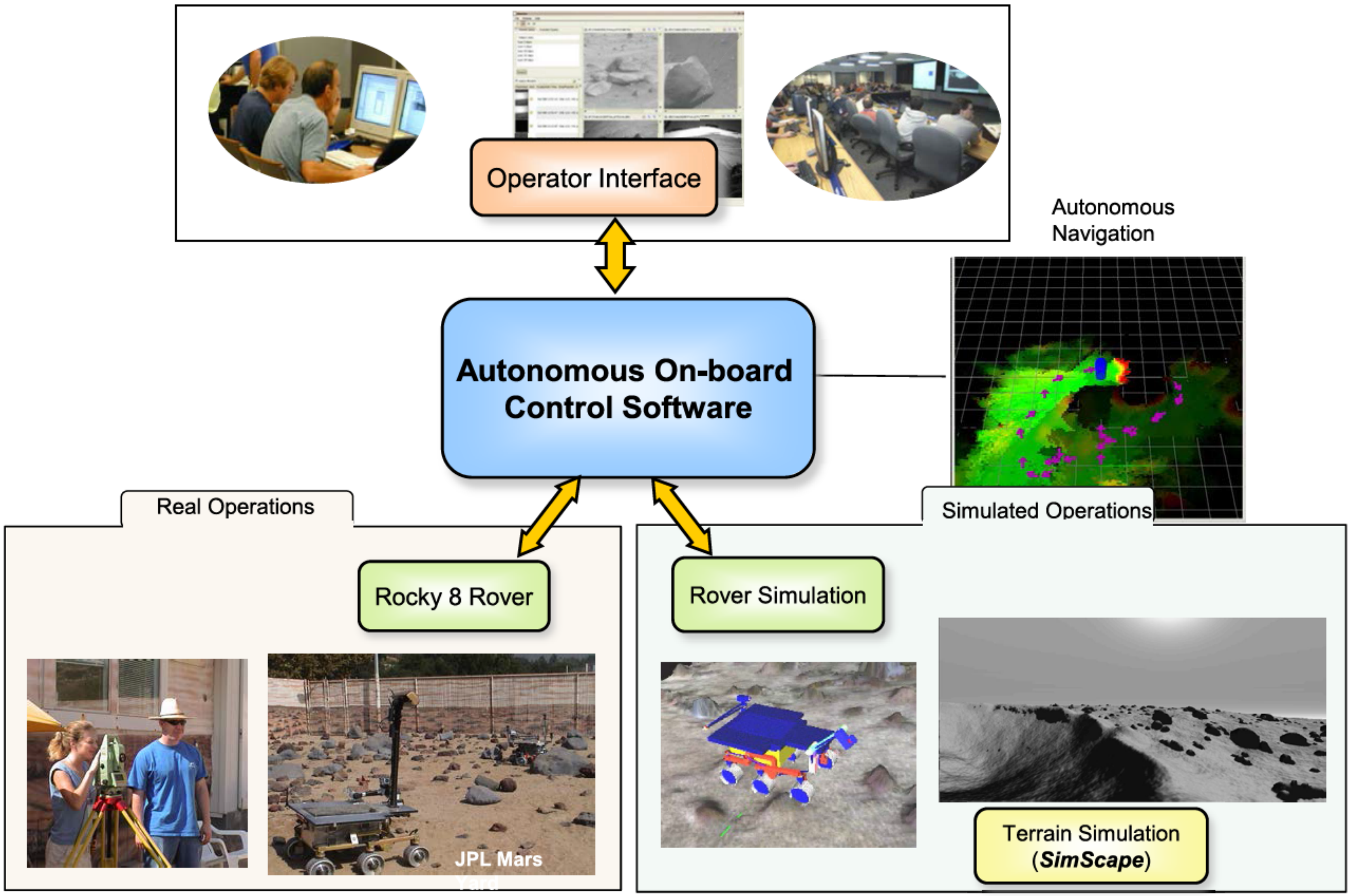
- **Blind Drive** (planned by ground)
- **Autonav** (uses on-board perception and terrain analysis)
- **Visodom** (uses on-board perception to detect slip)

Curiosity Rover Mobility and Autonomy

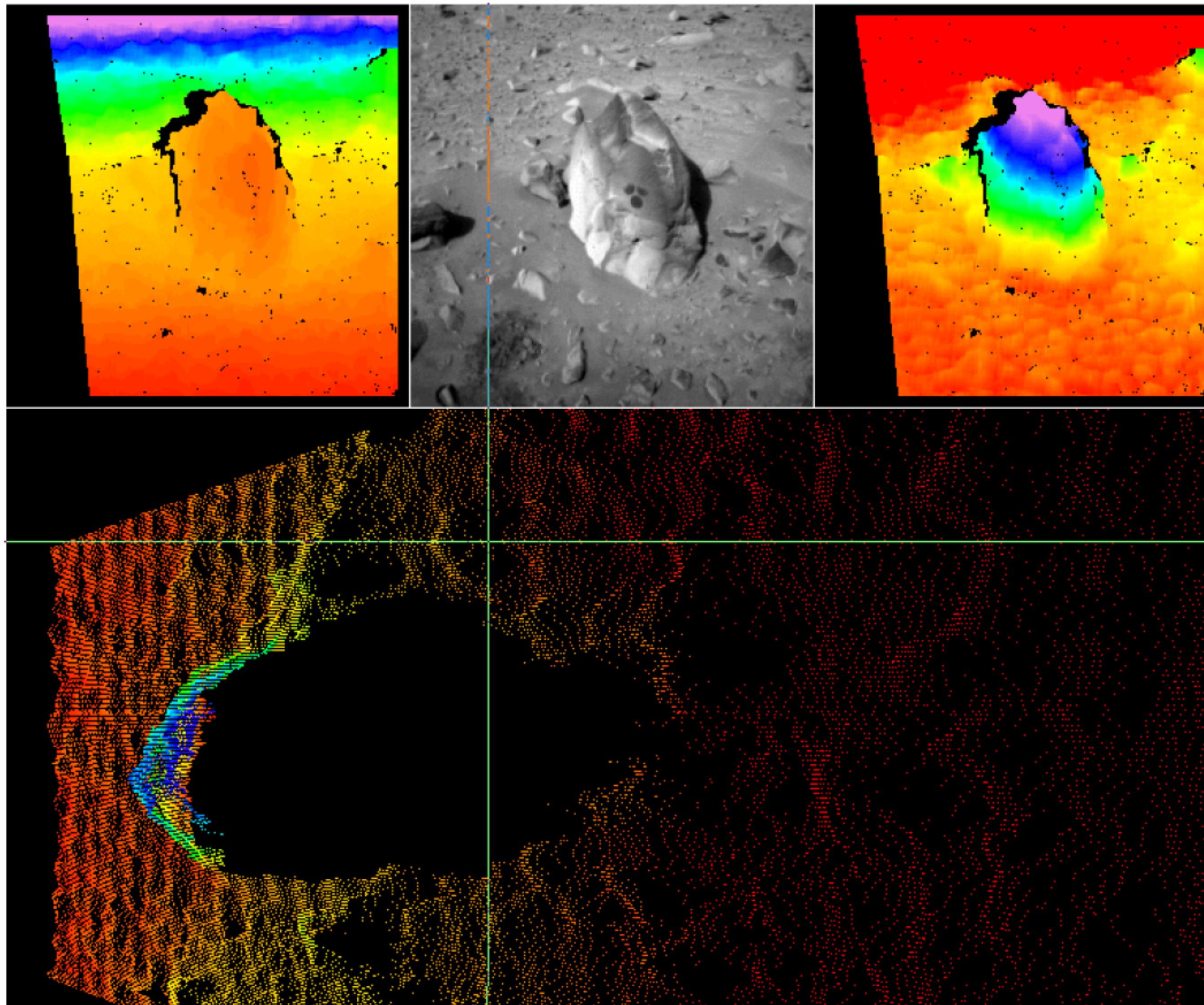


- Traversed ~750 m on relatively flat terrain with an average slip of 5%-6% and a max slip of 19%
- **Visual Odometry (VO):**
  - Helps with precision approaches to targets
  - Checks slips
  - Conducted around 500 visual updates at 1 m intervals and 20 deg for in-place turns
  - Soon, the rover would be able to turn on VO autonomously based on decreased yaw rate during turn-in-place, higher than normal average wheel currents, and/or higher body tilts.
- **Trafficability Assessment:**
  - Ran terrain assessment on four sols (so far), and one occasion that assessed an arc against a terrain
- **Auto-Navigation:**
  - Detecting and avoiding obstacles expected in future sols
- **Visual Target Tracking: ready for use on the rover**
- **Other capabilities:** rock characterization (AEGIS)
- Rover on its way to Mt. Sharp 10 km away
  - AutonavAt that point autonav expected to be used
  - Would be used following 40 m blind drive

End-to-End Robotic Systems

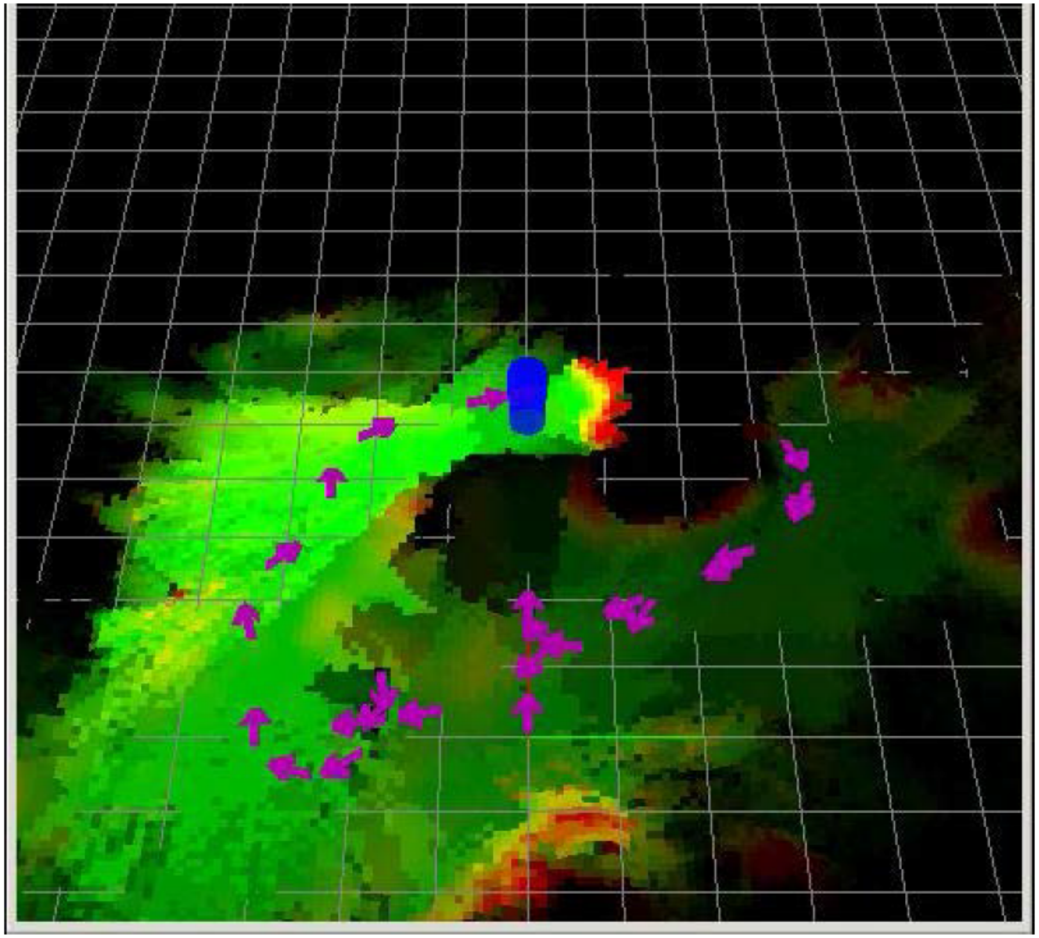


Perception

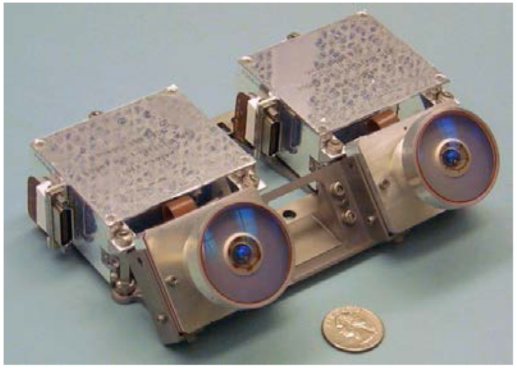


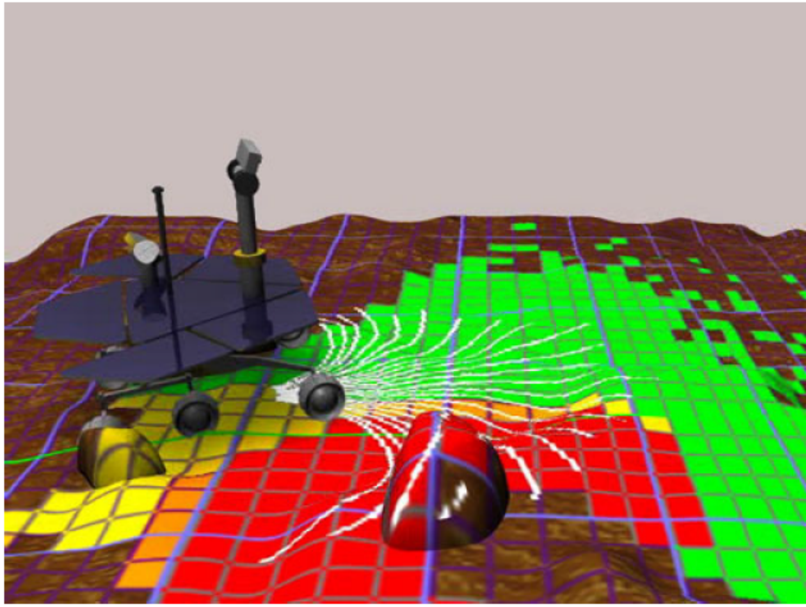
Credit: Mark Maimone, Todd Litwin, Larry Matthies

Terrain Analysis and Obstacle Detection



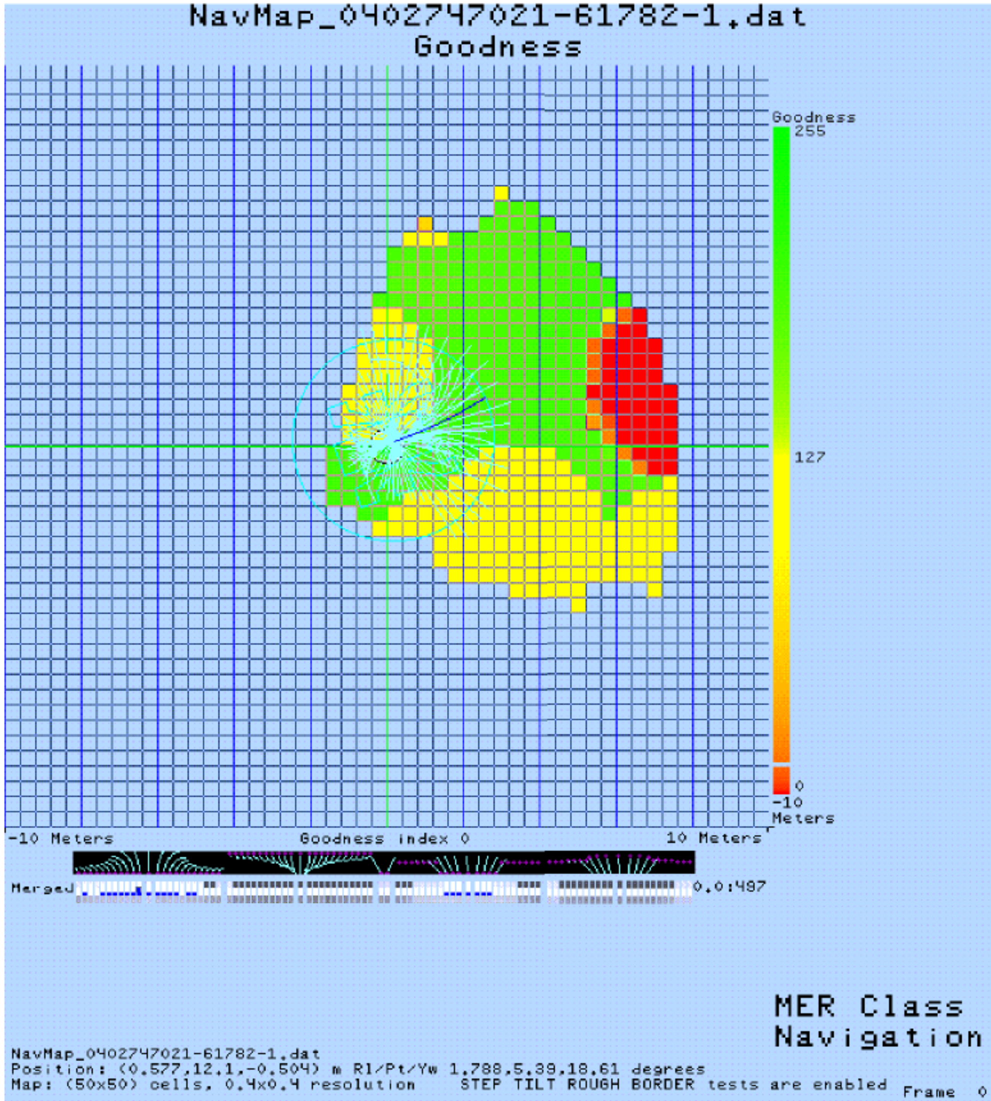
Credit: CLARAty - JPL/Carnegie Mellon

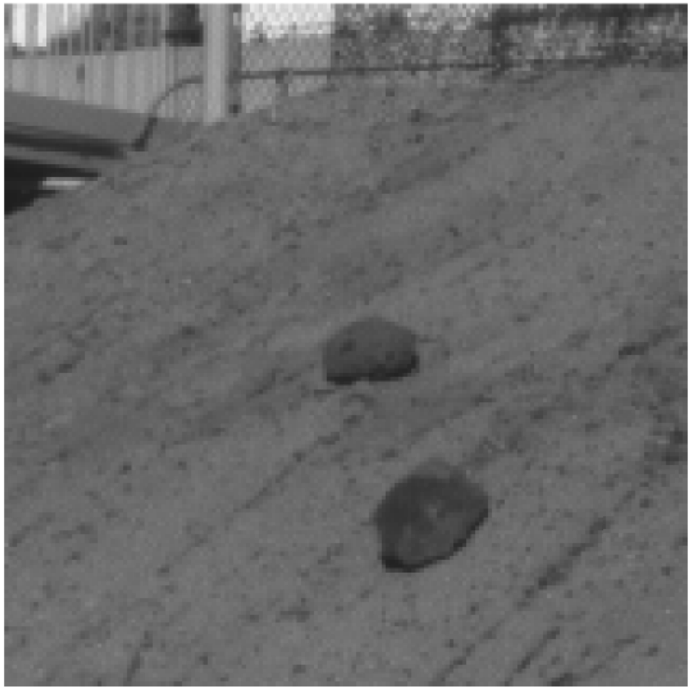




Credit: JPL/GESTALT navigation

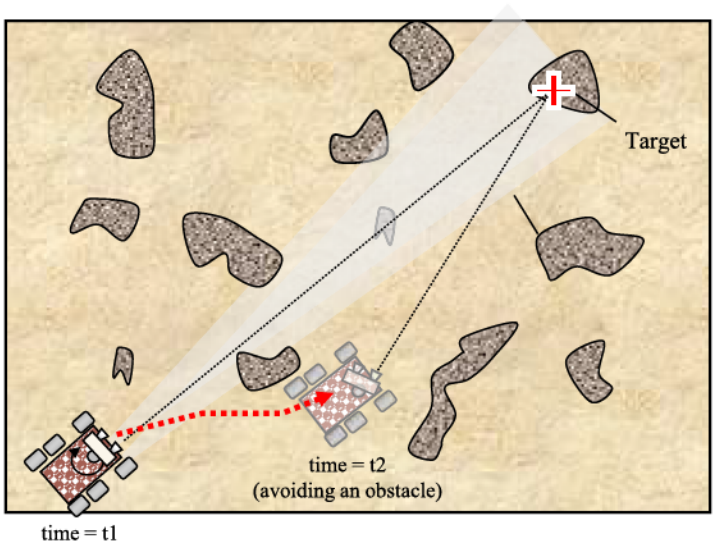
Navigation and Target Tracking



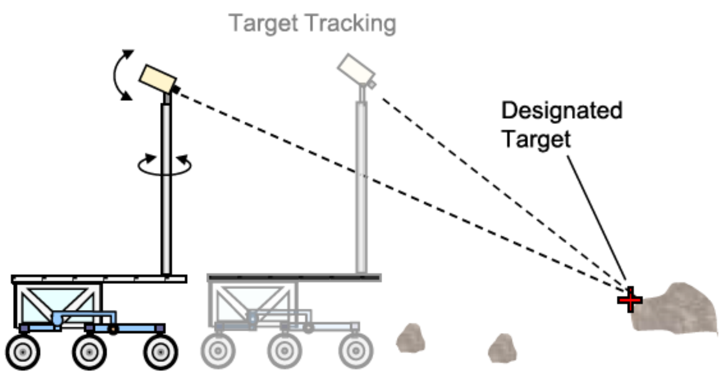


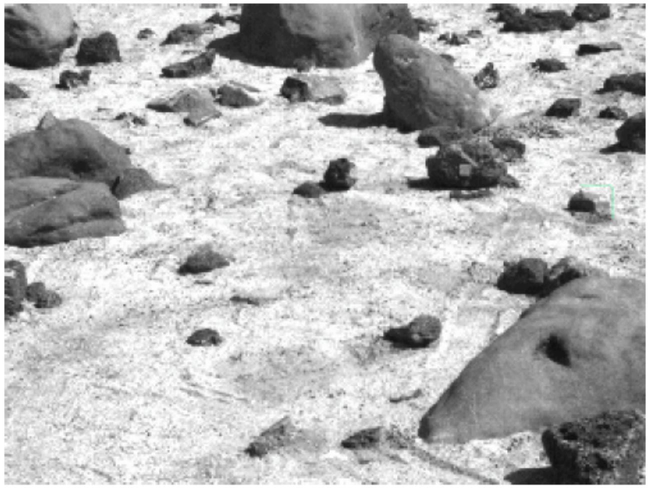
Autonomous Continuous Navigation

Goto and Precisely Touch or Manipulate



View from 4 mm camera





View from 16 mm camera

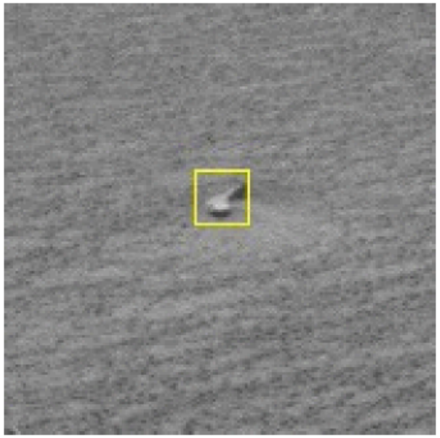
Navcam image used for Target Selection

Target selected at the center of rock

Approximate rock size
= 4 m target distance
* 20 pixels
* 0.85 mrad/pixels
= 6.8 cm

Opportunity Mars Exploration Rover (MER)

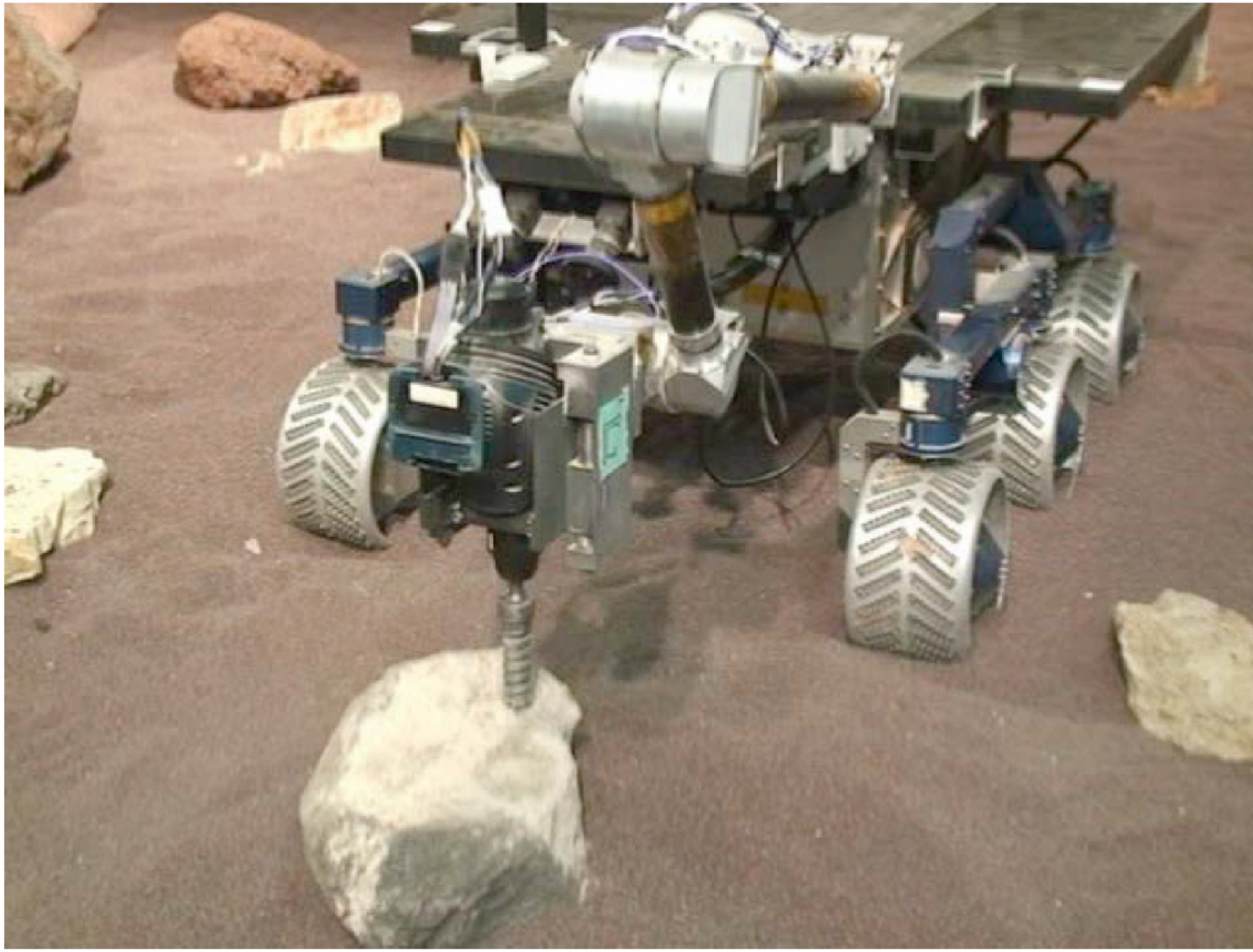
Victoria Crater



Courtesy of Rover Planner Matt Heverly / Won Kim

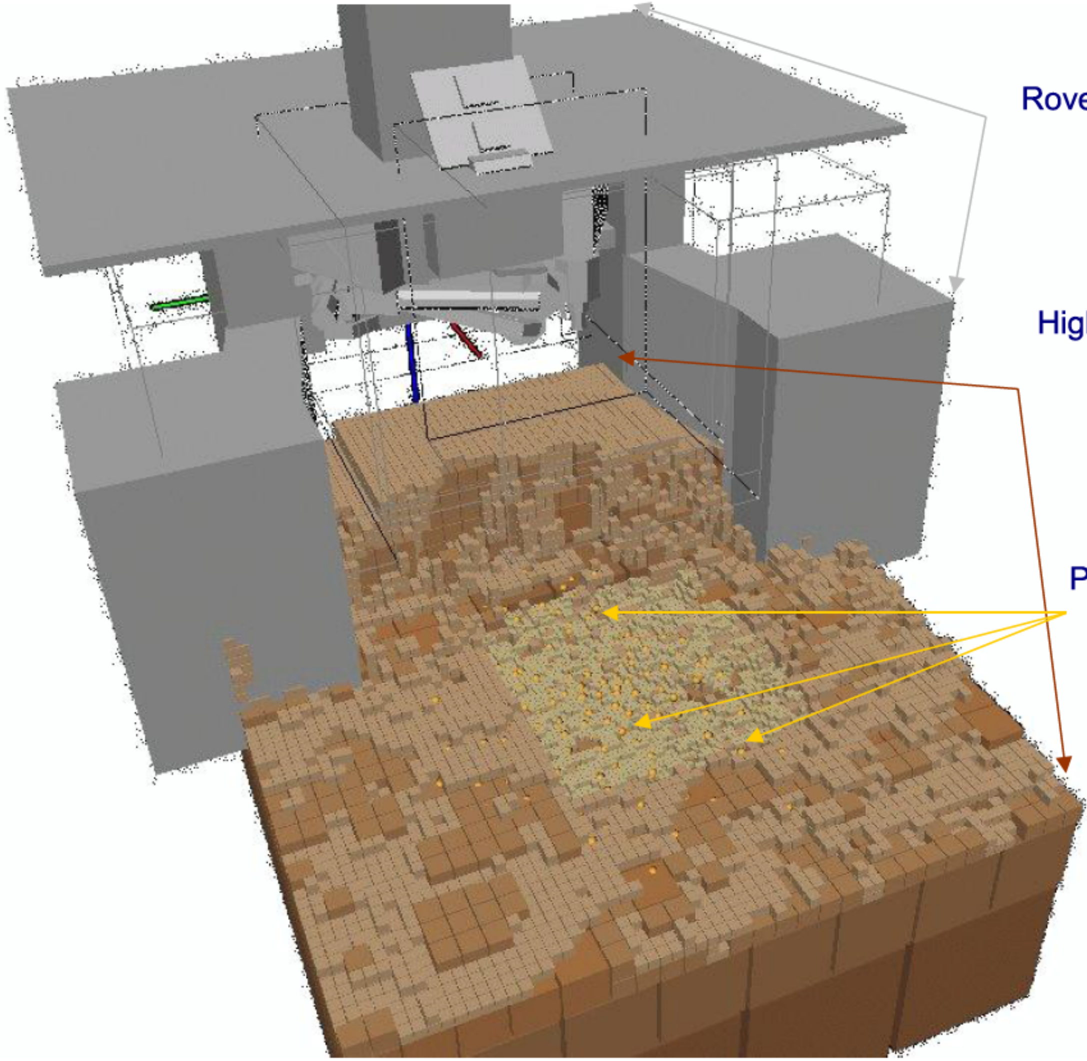
Jet Propulsion Laboratory
California Institute of Technology

Manipulation and Sampling



Mars 2018 Technology Demo, P. Backes (PI) (2012), Nick Hudson

Detecting Arm Collisions

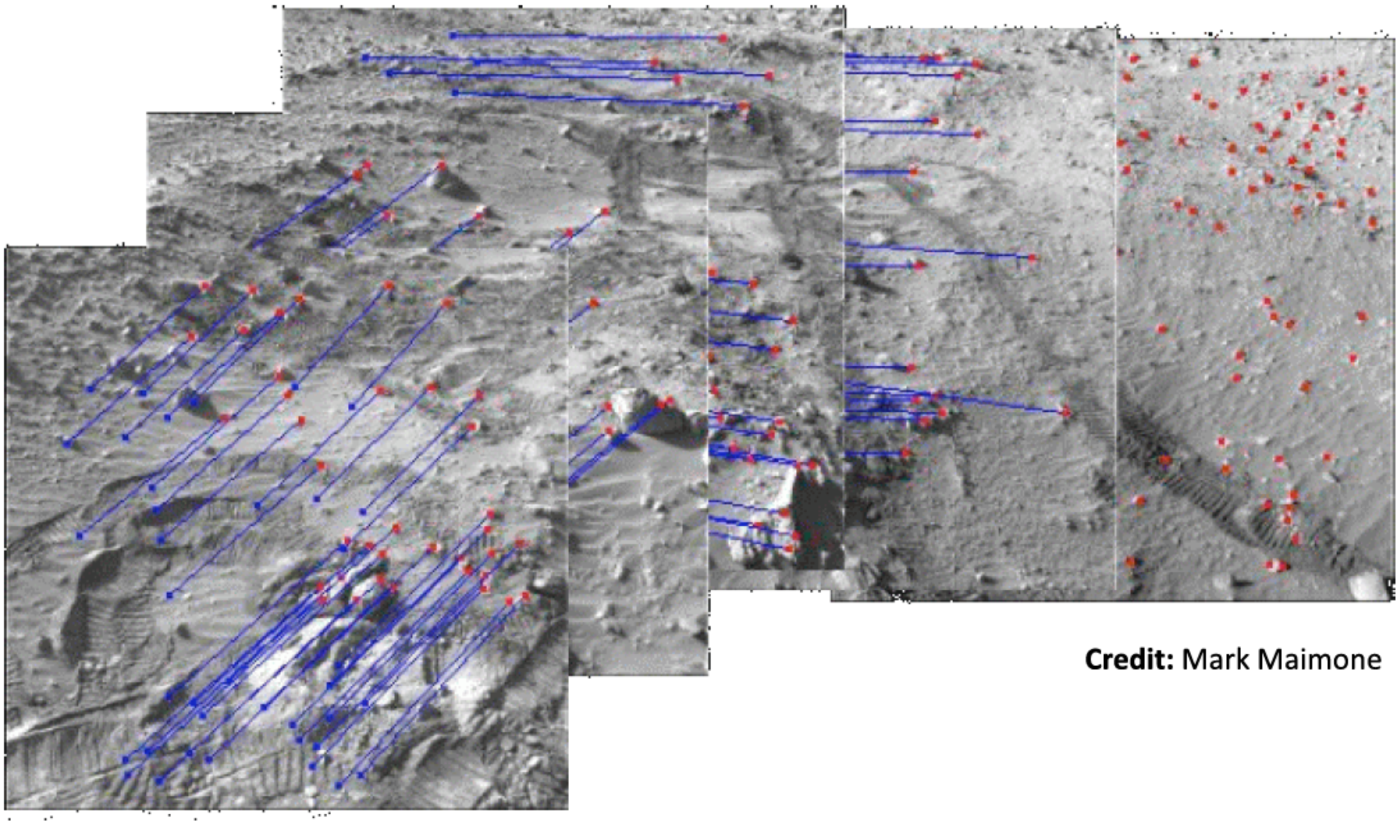


Rover Exclusion Zones

High resolution terrain model processed onboard

Potential IDD Placement targets

Visual Odometry



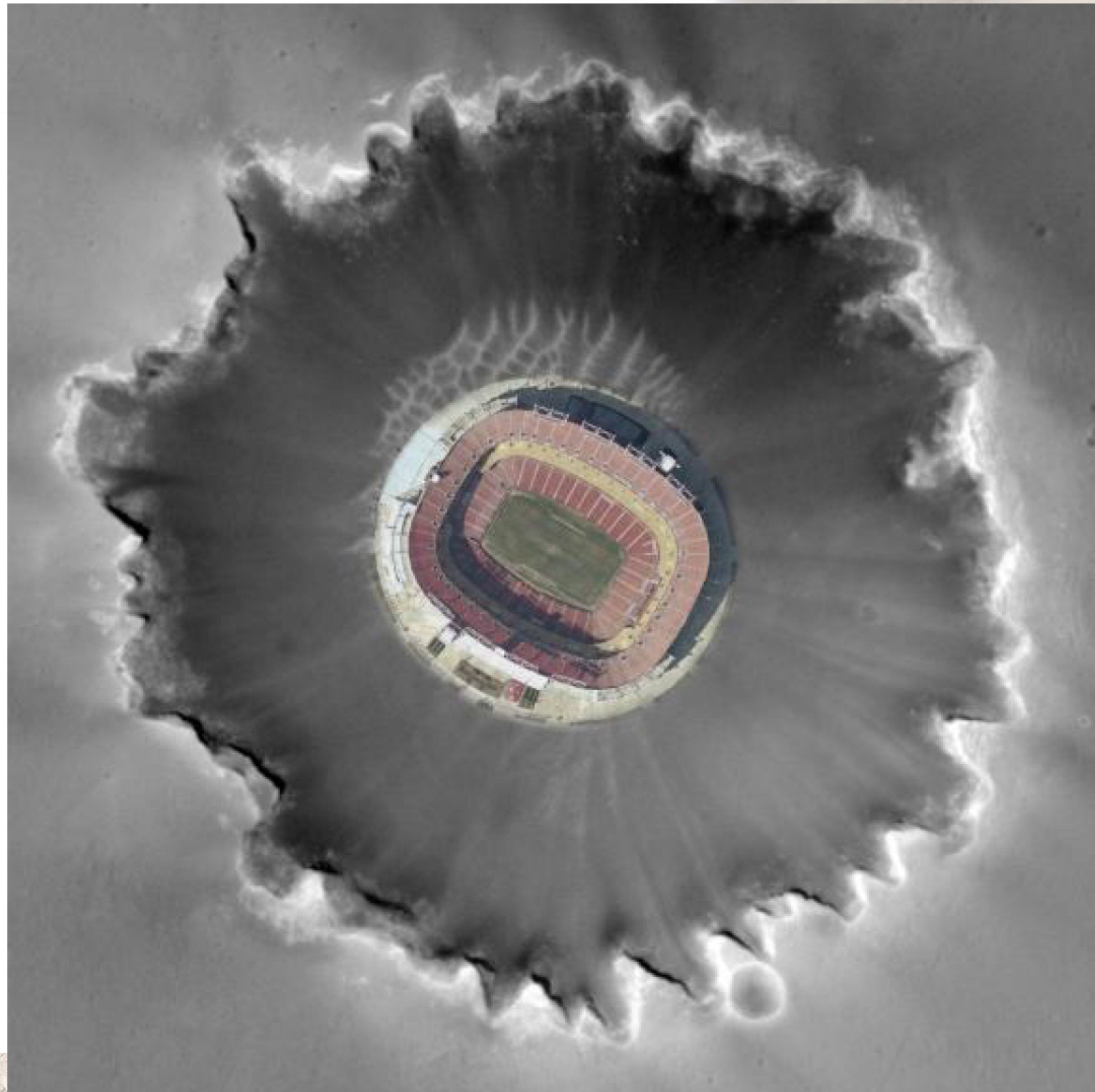
Credit: Mark Maimone

Tracks natural and distinct terrain features. Correlates features between successive frames to estimate rover's motion.

RECENT DISCOVERIES

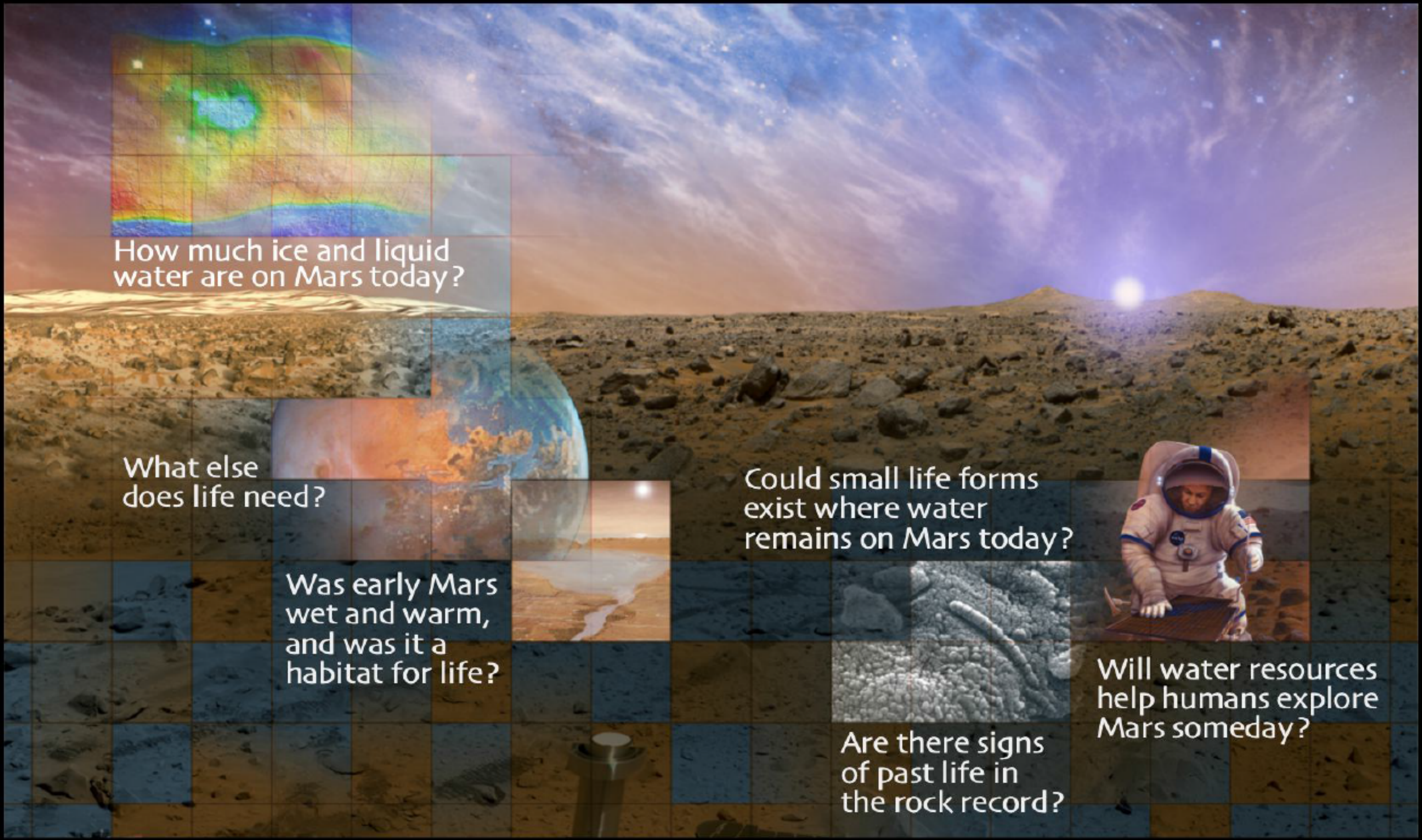
WHERE DO WE GO FROM HERE?

Jet Propulsion Laboratory
California Institute of Technology




NASA/JPL/Cornell

“Follow the water” to potential habitats.



Extreme Terrains?

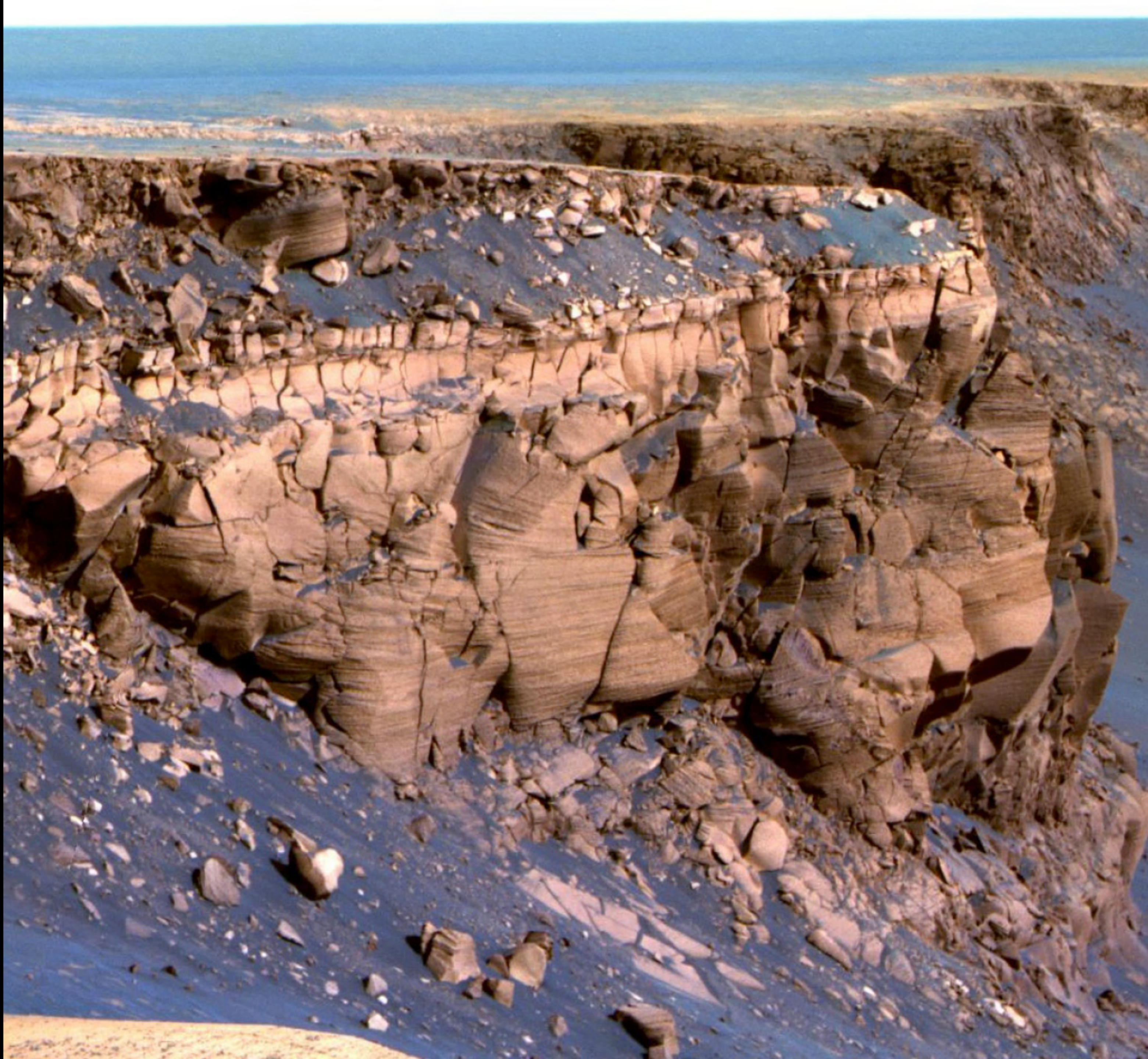
- Terrains with **extreme topographies** such as craters, fissures, canyons, gullies, caves and layered terrain may be of significant interest to both scientific and human exploration
- In-situ **science measurements** and **sample analyses** would be a key element

Mars

Cape St. Vincent, Victoria crater

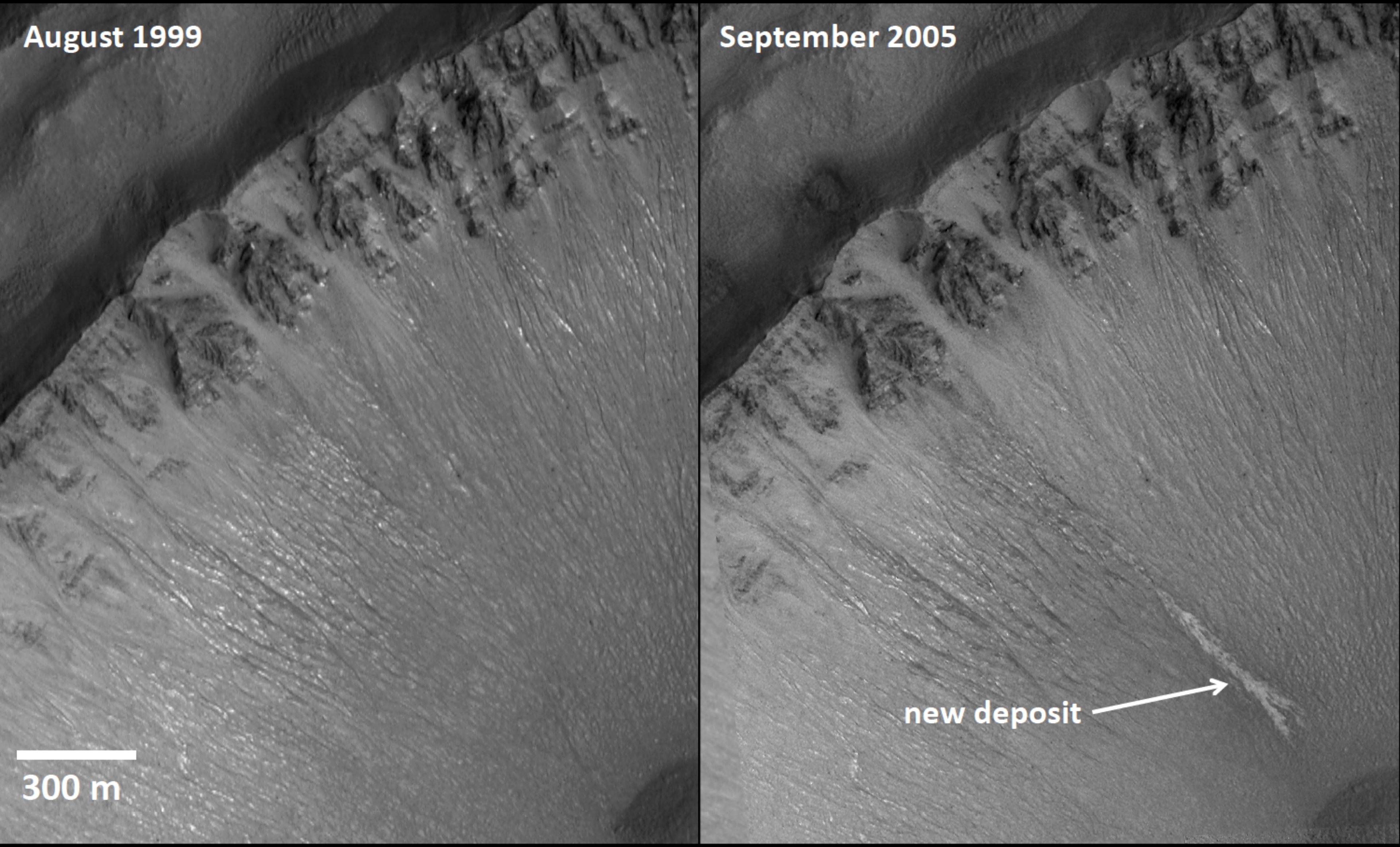
False color

Near vertical cliffs



Credit: MER – Opportunity Rover

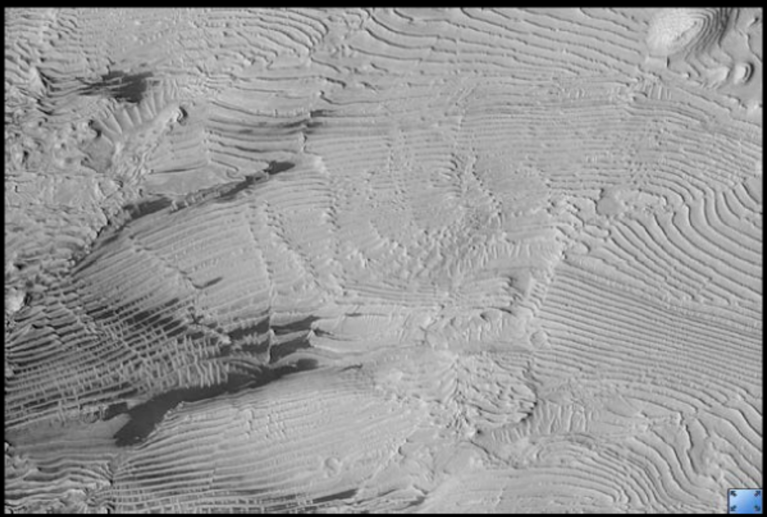
Mars



Surface activity in Unnamed crater in Centauri Montes

Mars

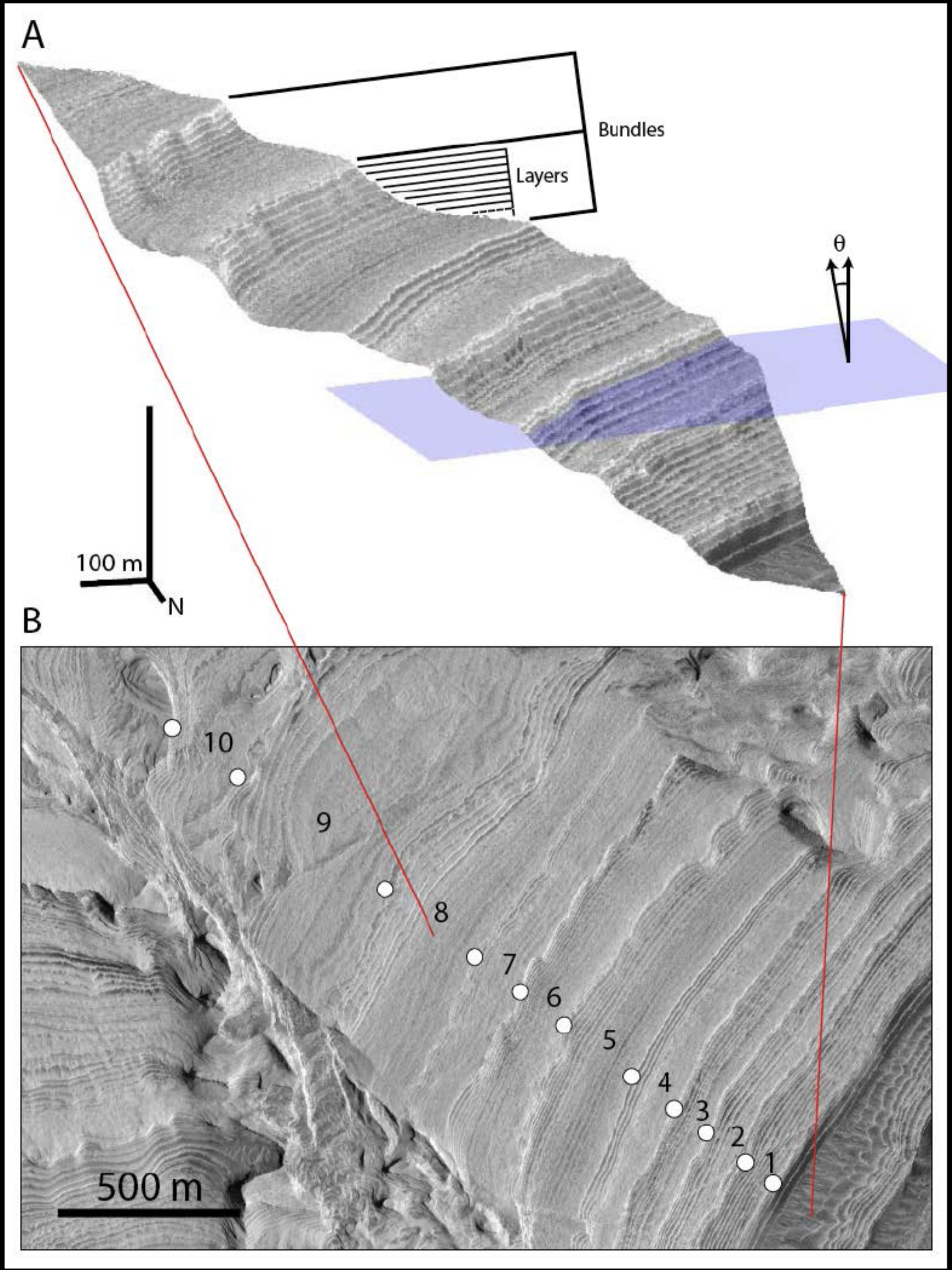
Faulted layers in impact crater in Meridiani Planum



Layers with height of
10 m – 20 m
and slopes up to
60˚ – 70˚

Credit:

- K.W. Lewis, et al, “Quasi-Periodic Bedding in the Sedimentary Rock Record of Mars,” Science 5, 2008
- Mars Reconnaissance Orbiter HiRISE

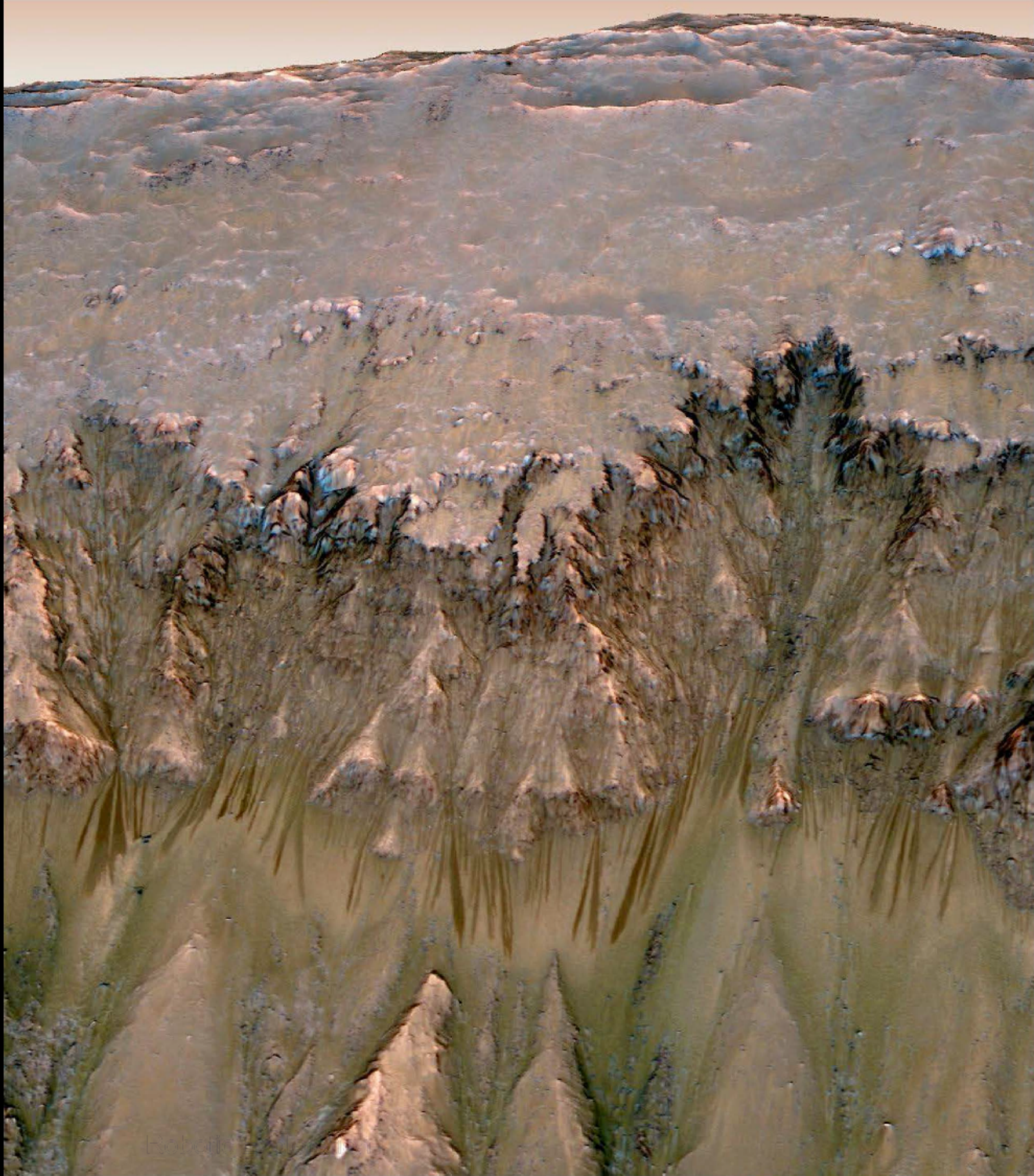


Mars

Flows in Newton Crater

Recurring slope lineae (RSL) appear during warm seasons

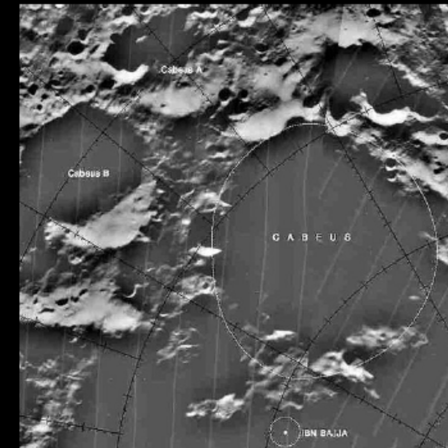
Narrow flows
0.5 m – 5 m
On steep slopes
25° – 40°



Credit: Mars Reconnaissance Orbiter HiRISE - August 4, 2011

The Moon

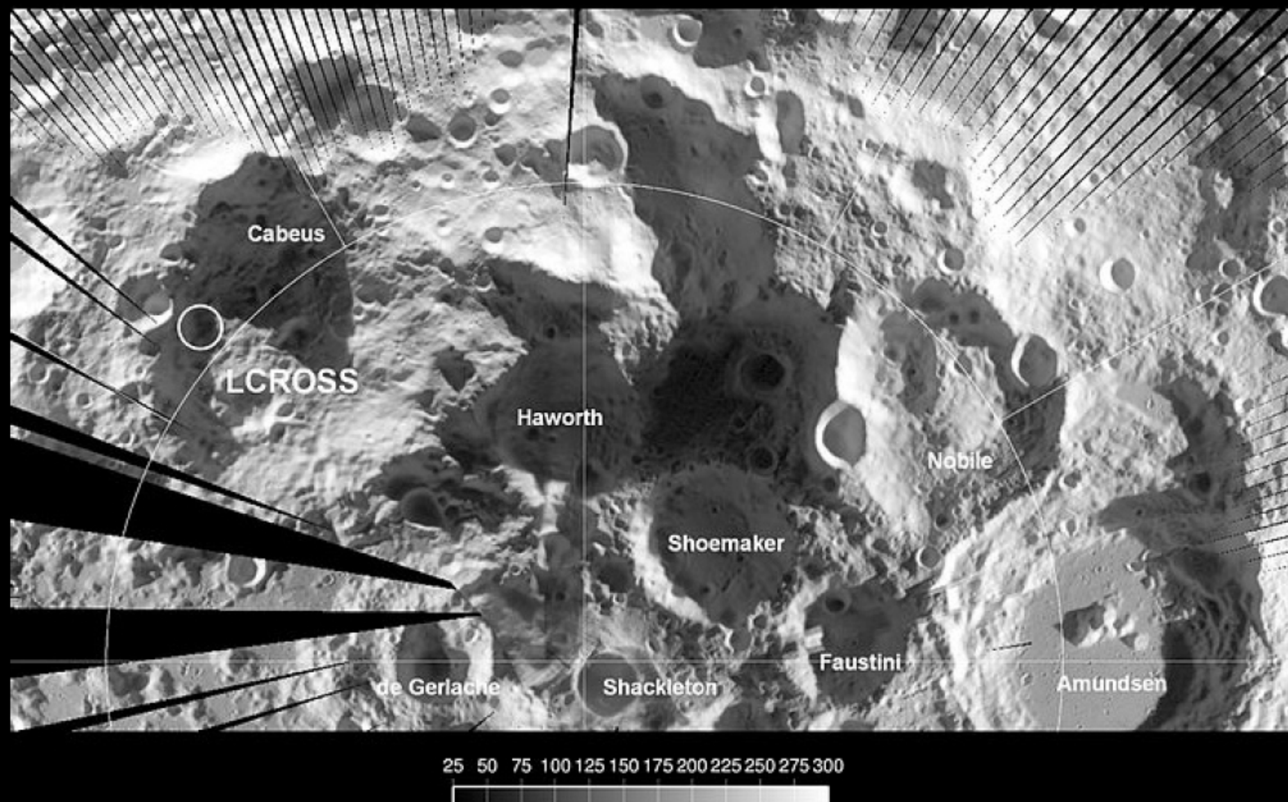
Evidence of water ice



Lunar South Pole

Heavily cratered surface and cold traps (deposits within craters)

Cold traps temperatures 40 K – 70 K

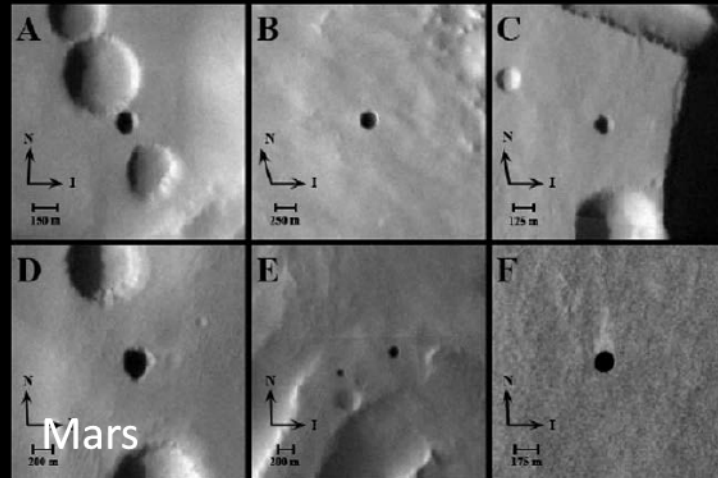


Diviner Channel 8 Brightness Temperature Map (K)

Credit:

- Lunar Reconnaissance Orbiter – Diviner

Mars
The Moon
Earth



Dark spots believed to be caves

Vertical walls
No surface of repose

Credits:
- (Mars) G. Cushing, et al, (2007), THEMIS observes possible cave skylights on Mars, Geophysical Research Letters, 34
- (Moon) NASA/GSFC/Arizona State University
- (Earth) USGS, Hawaii and Arizona

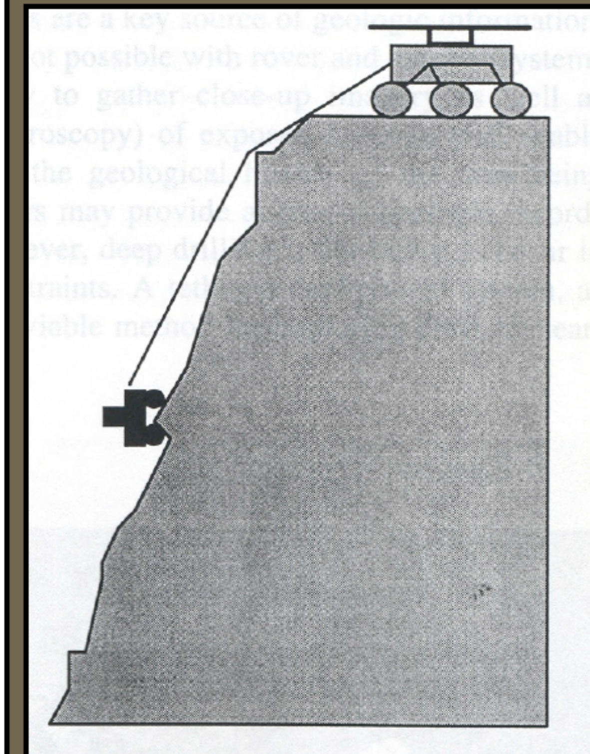
CONCEPTS & TECHNOLOGIES

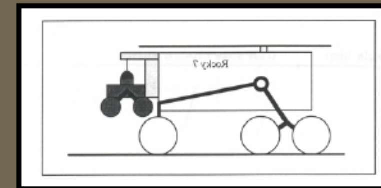
Concepts and Systems

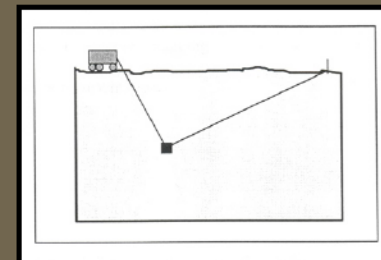
1994 Dante II – CMU

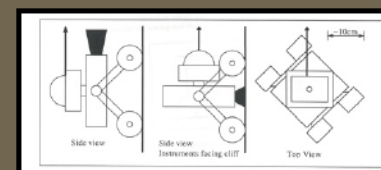
J. Bares, D. Wettergreen, IJRR 1999

- Tethered walking robot
- Explored Mt. Spurr
- Robot-side winch
- During ascent, fell on its side and was unable to right itself.







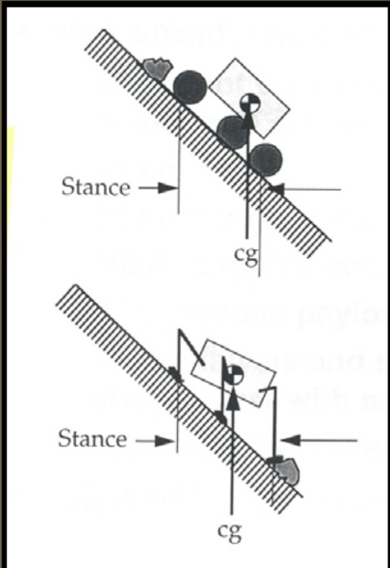


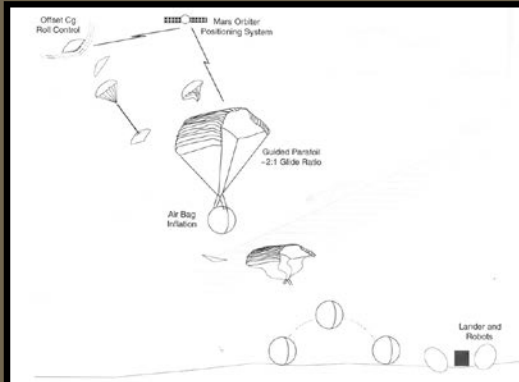
1998 Cooperative Robotic Cliff Exploration

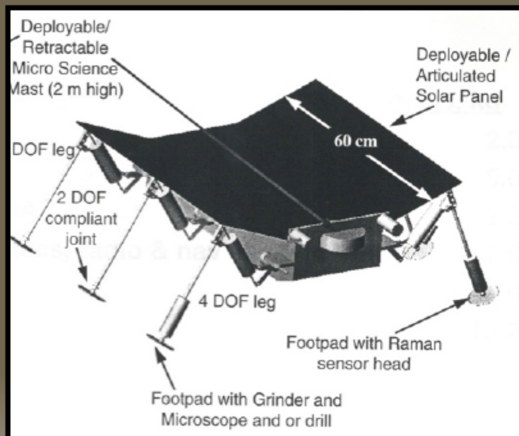
R. Welch, P. Fiorini, R. Volpe, B. Wilcox - TRIWG Proposal

- Marsupial rover concept
- Traverse >75 m on near-vertical terrain
- Nanorover deployed from a Sojourner class rover

Concepts and Systems







1999 Robotic Mission Concept for In-Situ Stratigraphy

Terry T. Nock

- Chemical, mineralogical, and age dating measurements
- Sampling via drilling (ultra-sonic) and grinding
- Assumed precision landing
- Argued for legged mobility over wheeled; invertable
- Traverse range > 15 km on steep (<40º) rocky slopes
- Optional tether - Proposed mass: **15 kg**

2002 Dual Tether Cliffbot

P. Pirjanian, P. Schenker, et.al., ICRA 2002

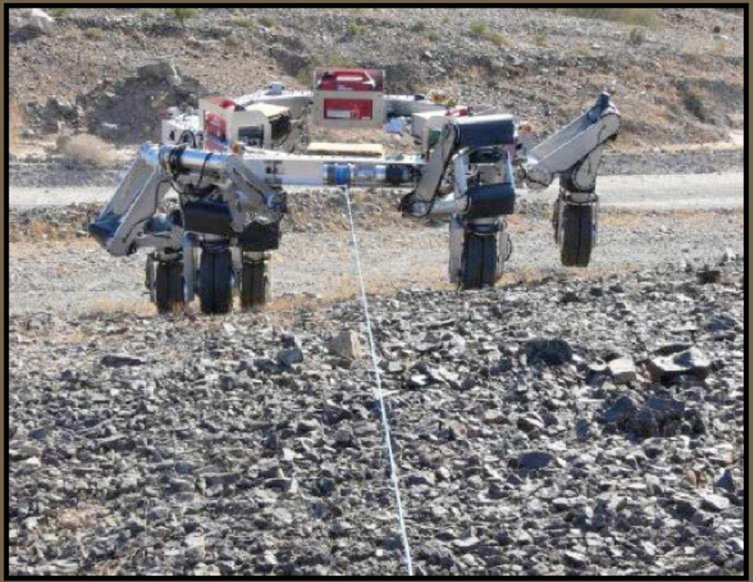
- Tethered wheel rover
- Two anchor-bots support winches
- Moves laterally when close to top
- Recon-bot observes/reports obstacles
- Winching from above causes tether abrasion.

Concepts and Systems

2007 SCARAB Lunar Rover

D. Wettergreen, R. Whitaker, CMU

- Objective: to demonstrate combined drilling and science rover
- Designed to to explore Lunar polar regions (extreme cold temperatures, perpetual darkness, and intermittent communications)
- Untethered wheeled rover with active suspension



2008 ATHLETE Legged Lunar Robot

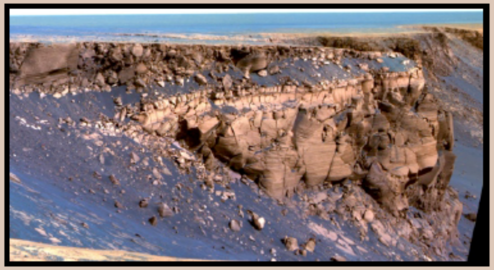
B. Wilcox, et.al. "Athlete: A cargo handling and manipulation robot for the moon," Journal of Field Robotics, May 2007. Tethered platform

- Legged Lunar Platform
- Legged and tethered mobility for steep terrain access
- Primarily fuel cell powered
- Mass: TBD kg

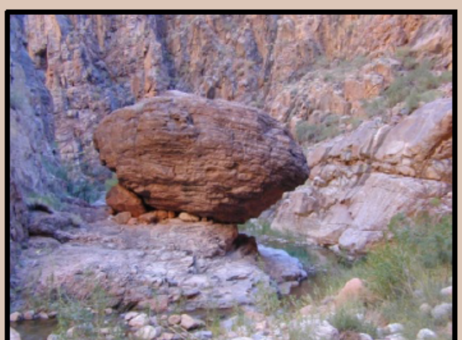
AXEL ROBOTS

Challenges

Terrain Challenges


Steep slopes and uneven terrain


Sinkage


Obstacles and boulders

Power/Comm Challenges


Intermittent Communication


Lack of direct sunlight

Thermal Challenges


Extreme cold

Design Requirements

- **Minimalistic**
- **Low-mass**
- **Compact**
- **Versatile**
- **Symmetric**
- **Robust**
- **Contained** (thermal)

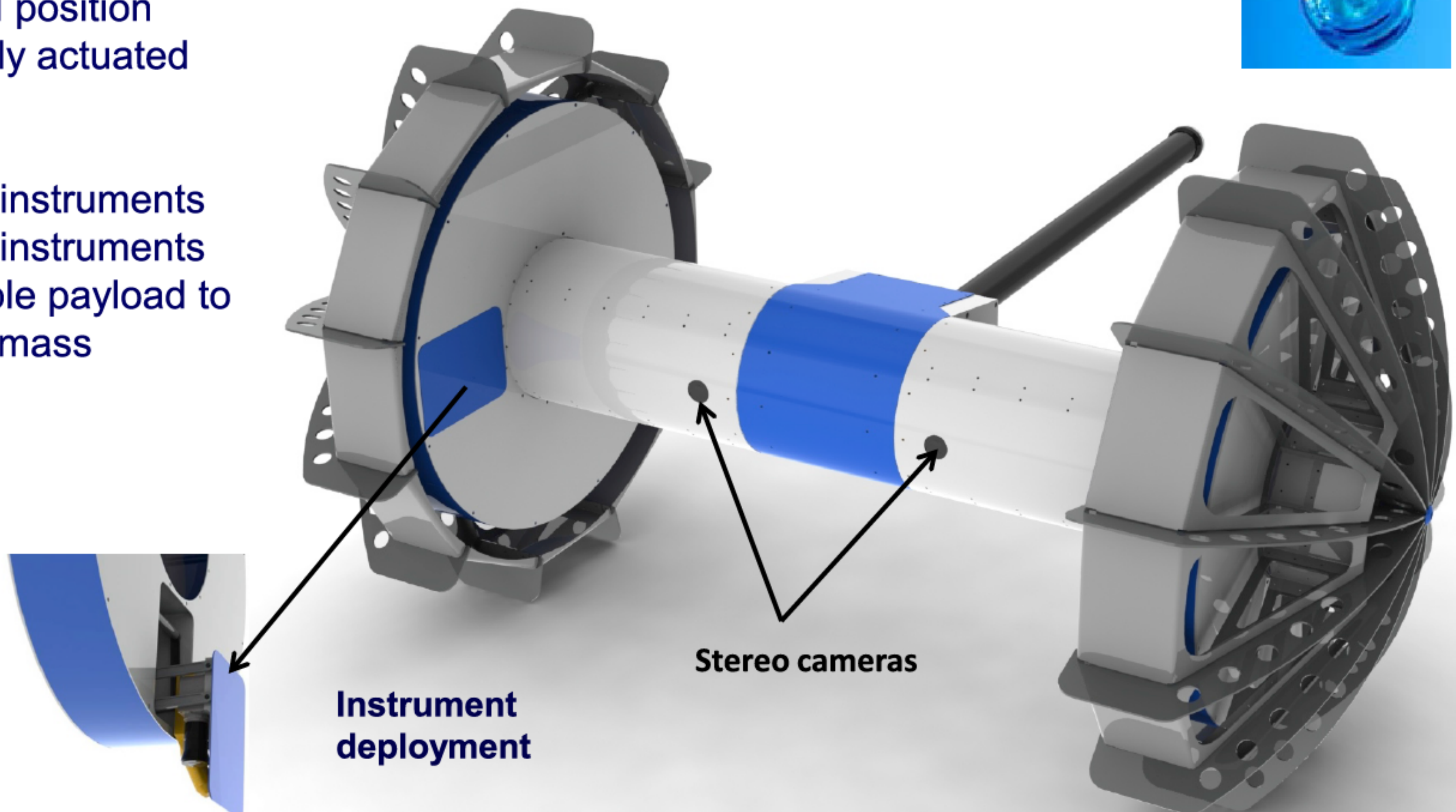
Lends itself to multiple copies for risk management given the extreme terrain objective

Axel Rover

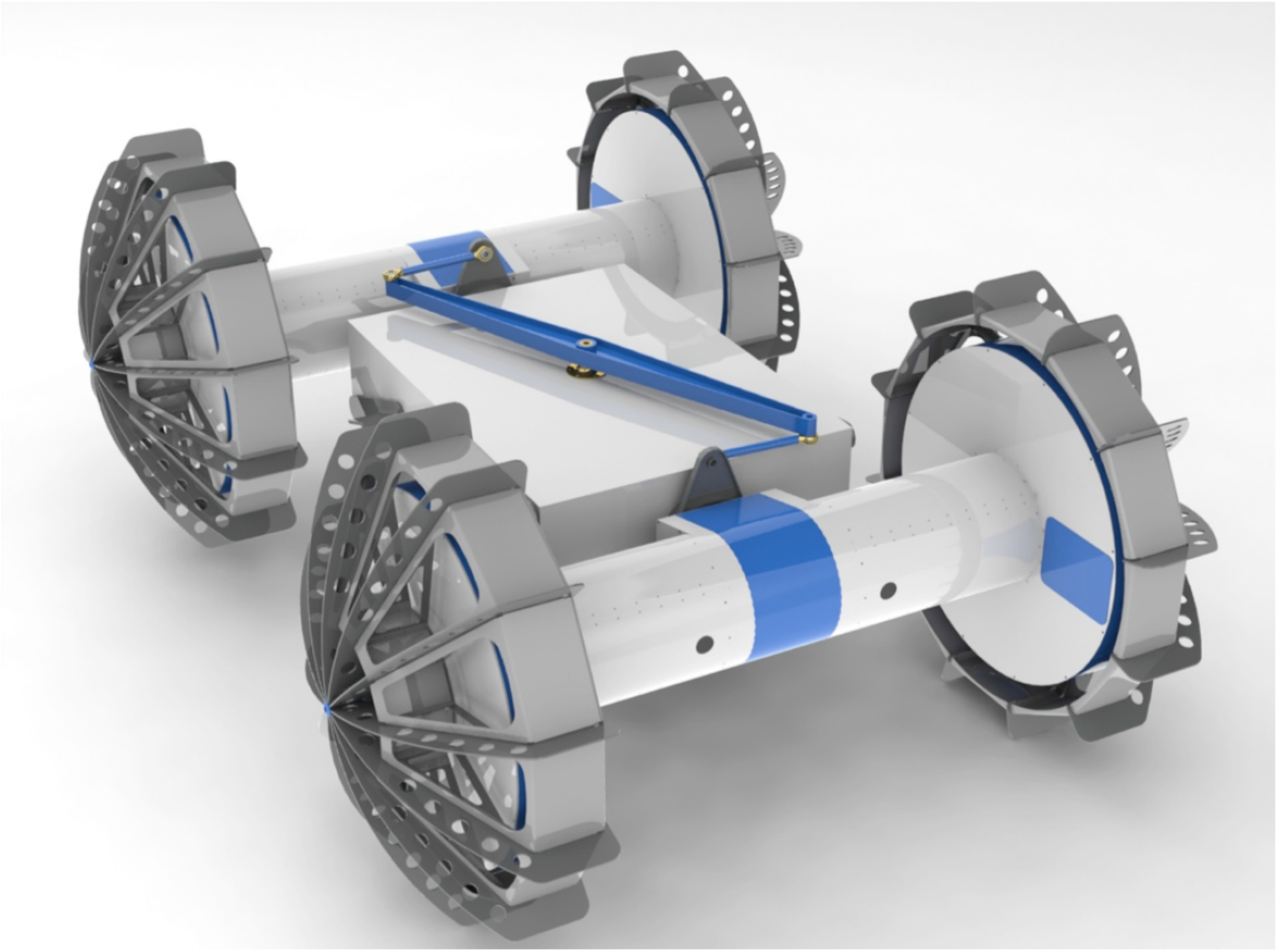
Works like a YoYo

Mobility
- With or without tether
- Inverted position
- Minimally actuated

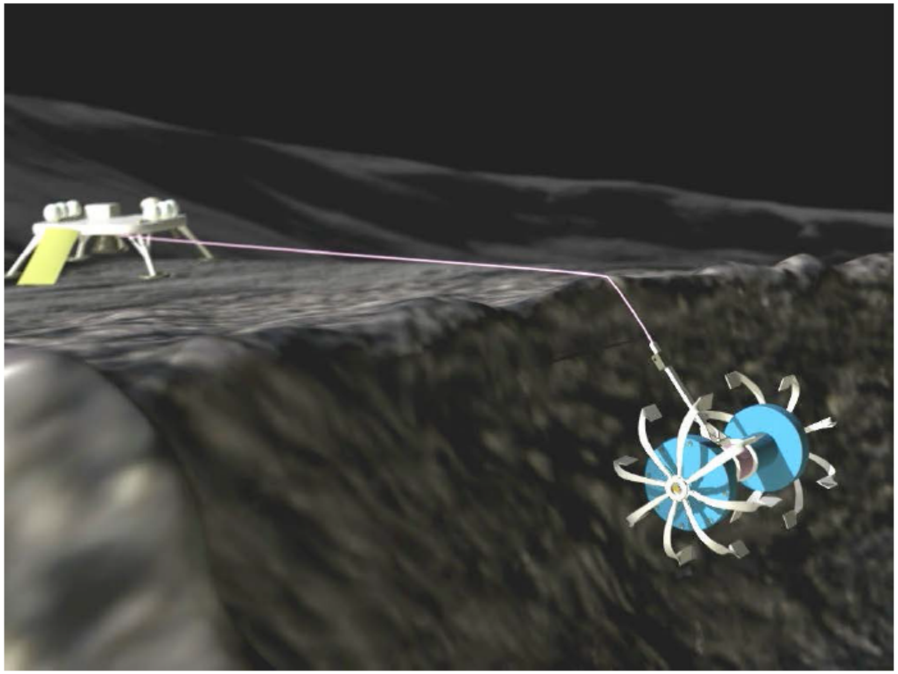
Science
- Up to 8 instruments
- Orients instruments
- Favorable payload to system mass



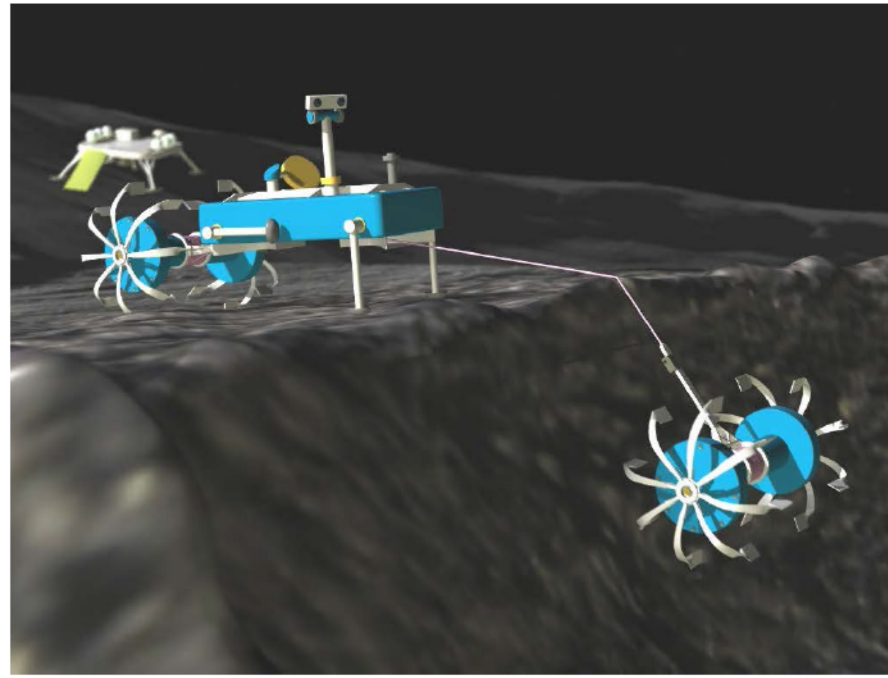
DuAxel



Systems Concepts

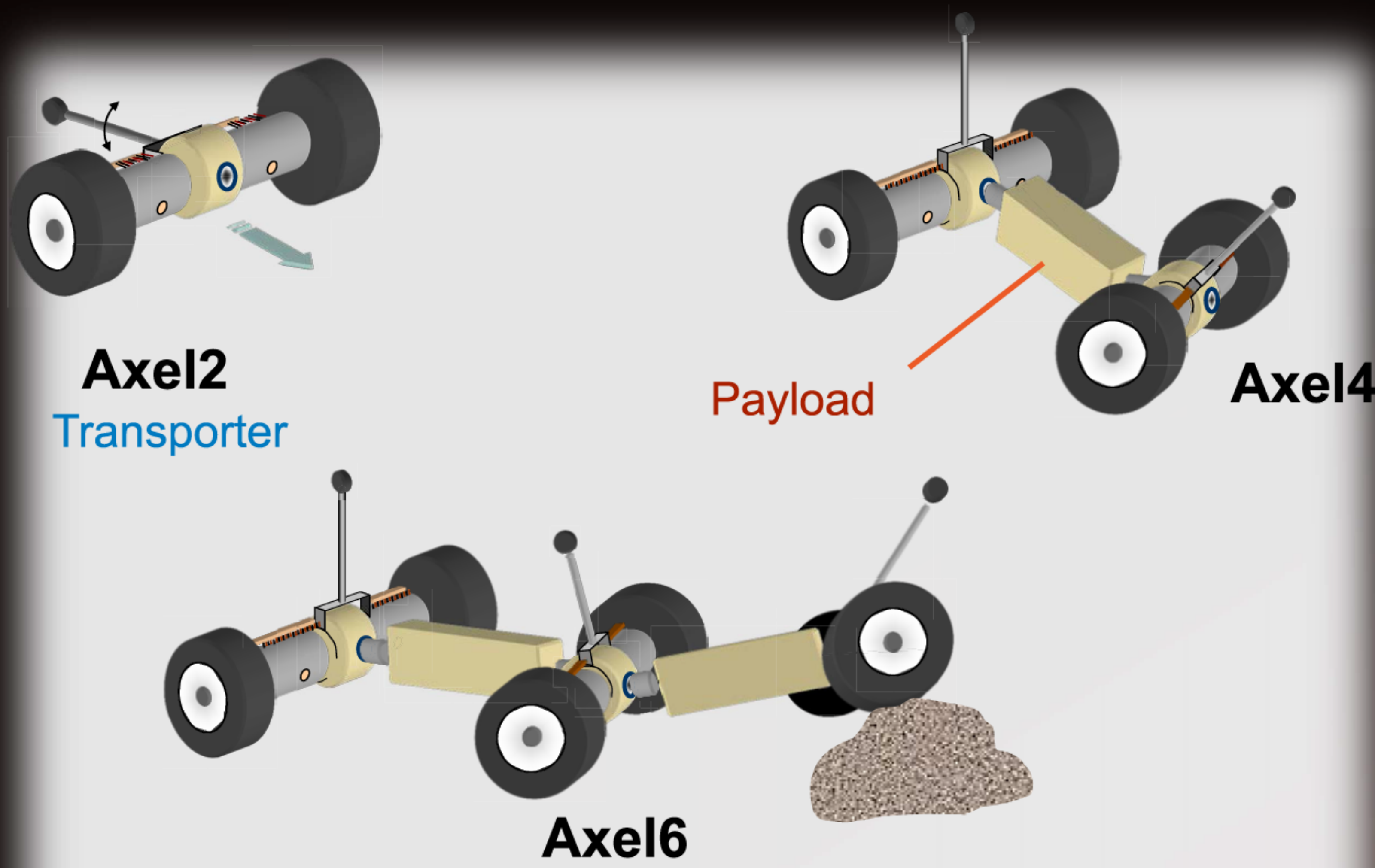


Axel
Fixed mother (lander)
mobile daughter (Axel)



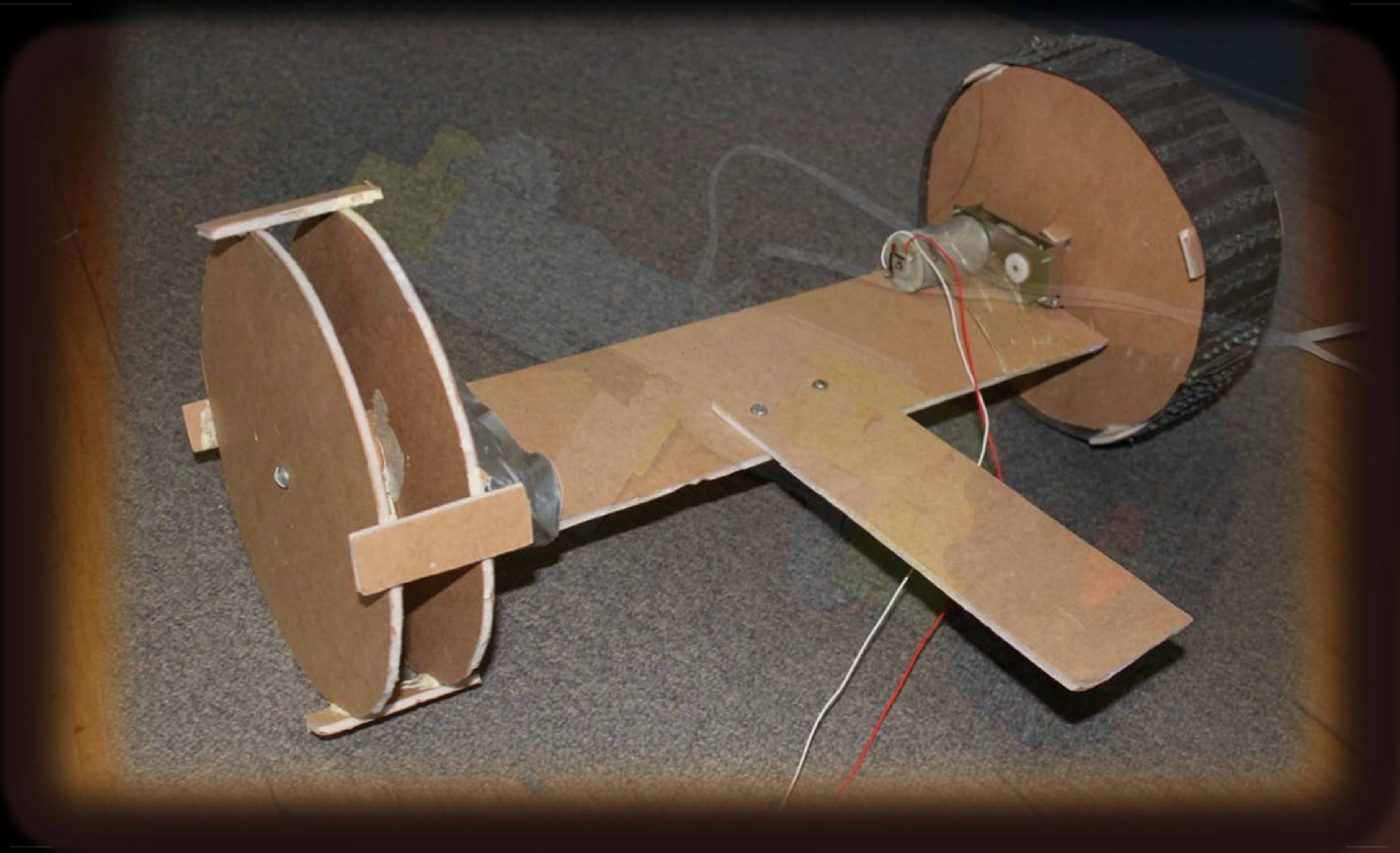
DuAxel
Mobile mother (untethered DuAxel)
Mobile daughter (two Axels)

Concept Evolution …

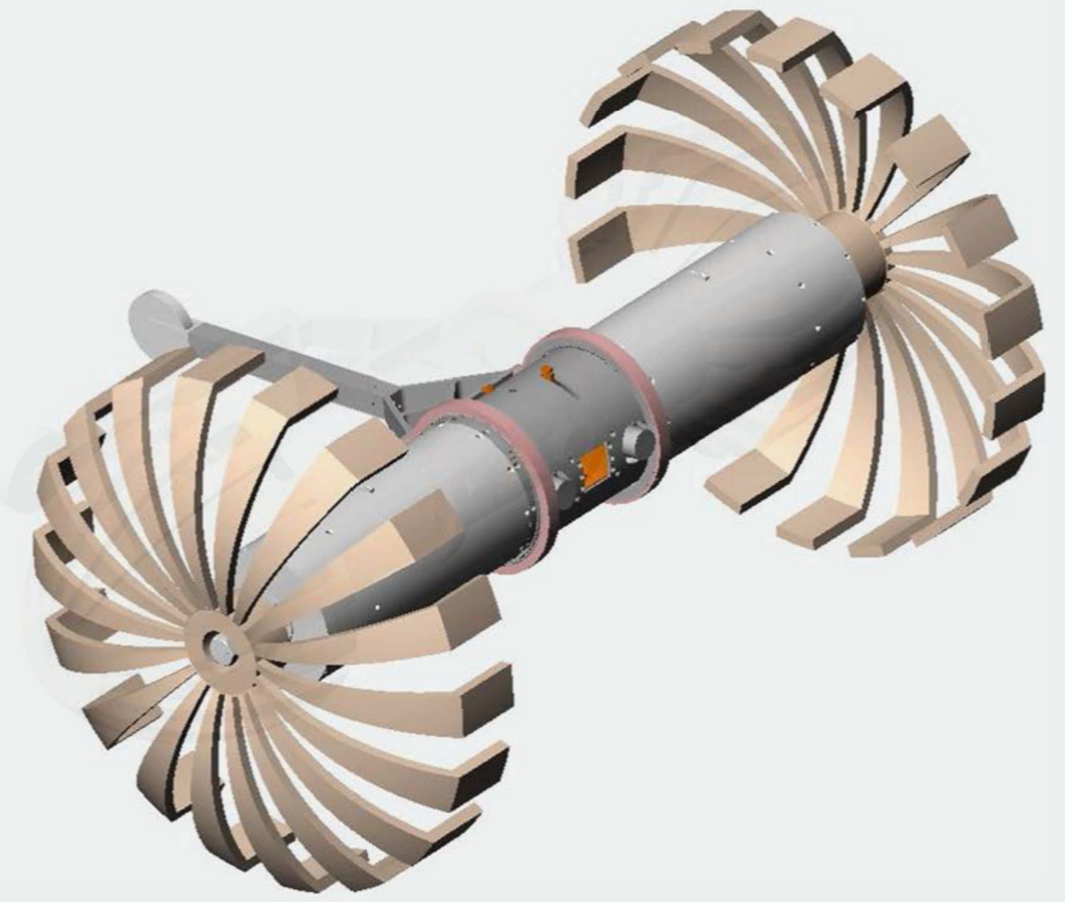


Key Concept - separate **payload** from **transporter**

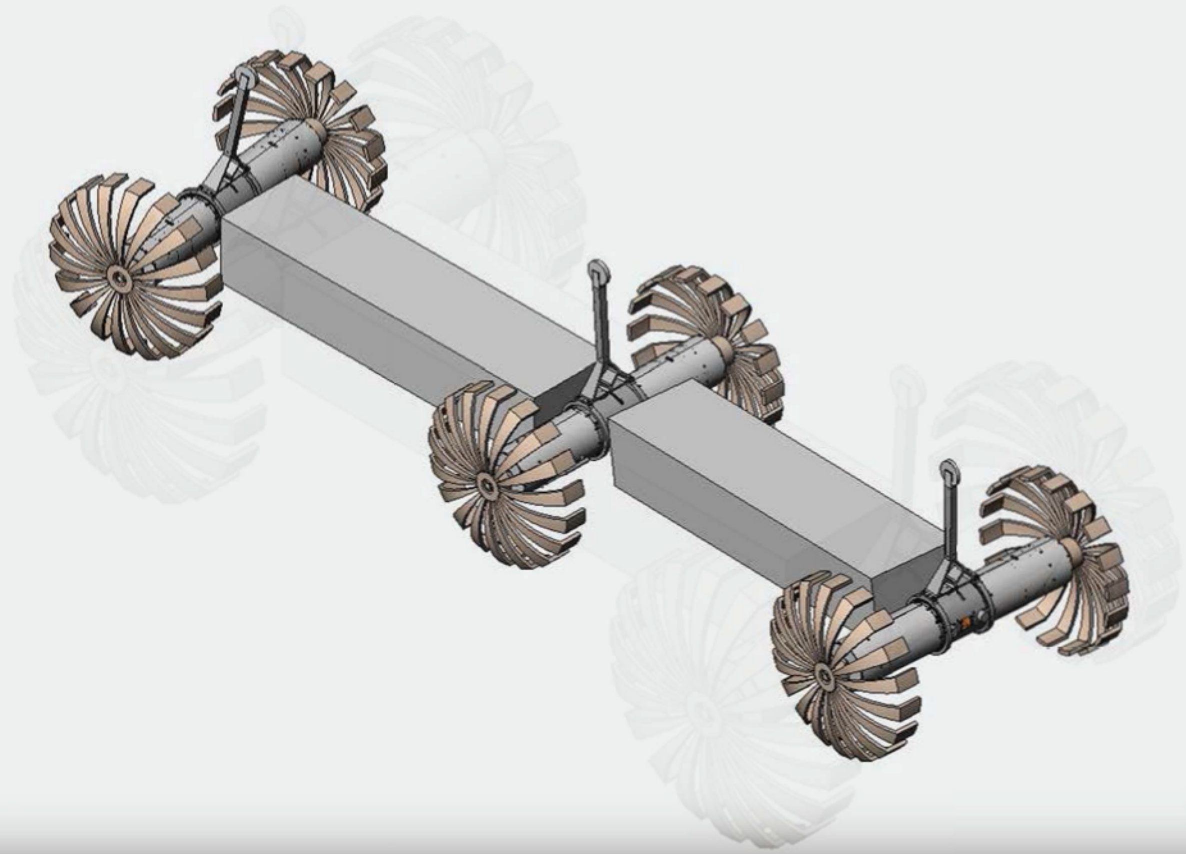
Independently conceived in 1999



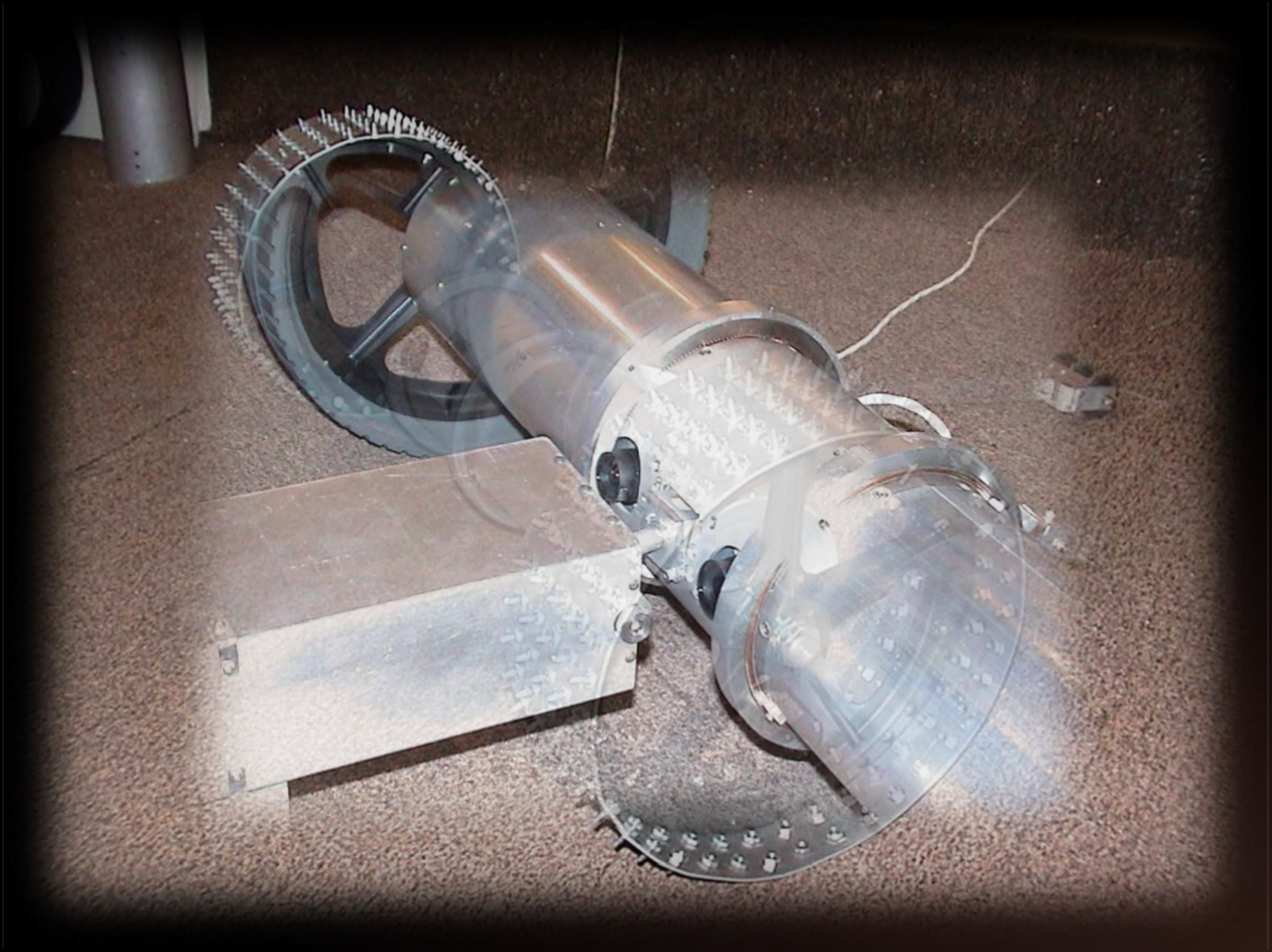
The very first prototypes (1999)



Axel version 1 designed in 2001



Mutli Axel rovers



Axel version 1 (2000)

With Caltech, adapted Axel version 1 for steep terrains (2006)

Axel version 2 (2006)

Axel version 2 (2006 - 2009)

Caltech demonstrated overcoming obstacles 90% of wheel diameter

Axel/DuAxel version 3 (2011)

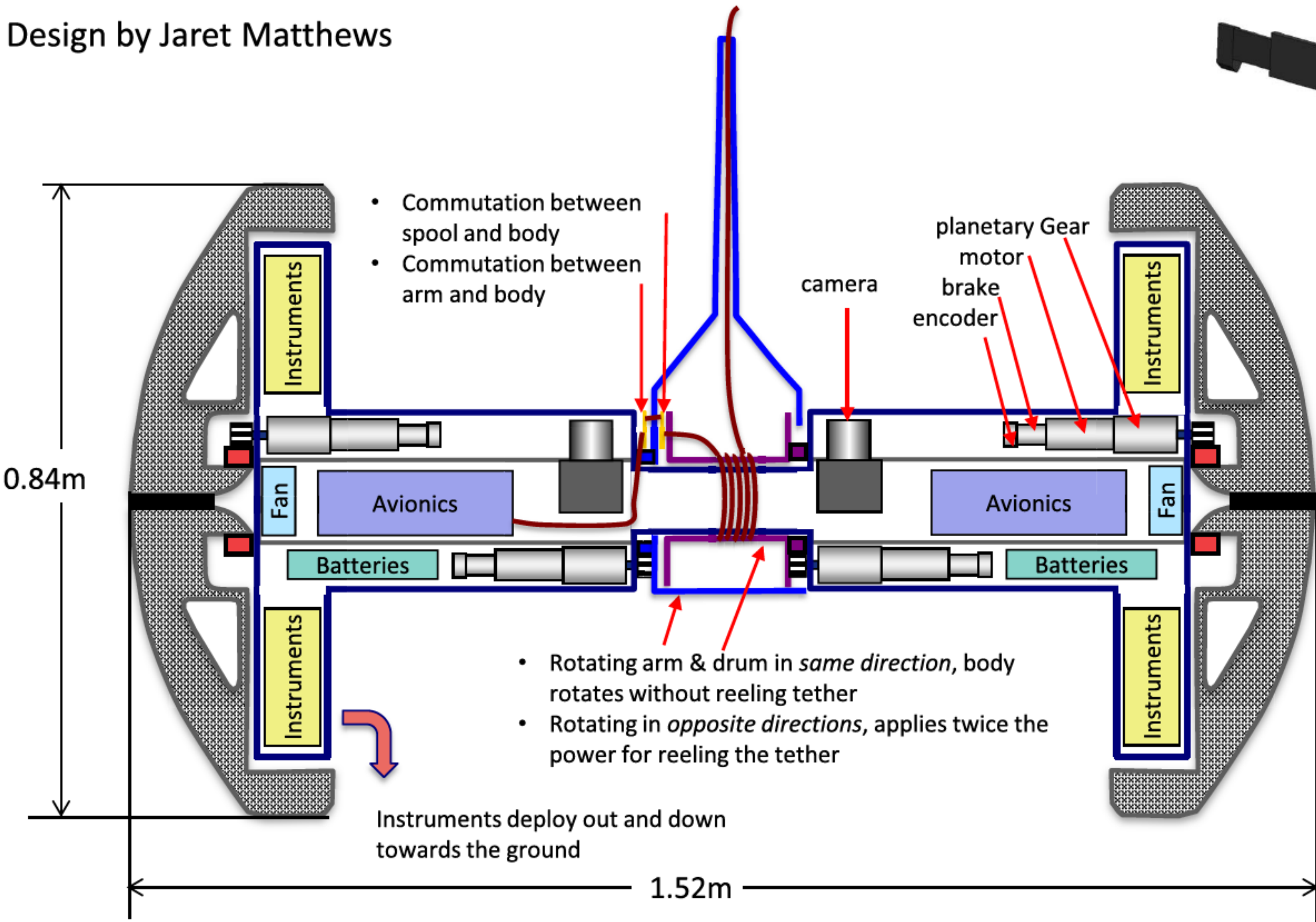
The beginning …

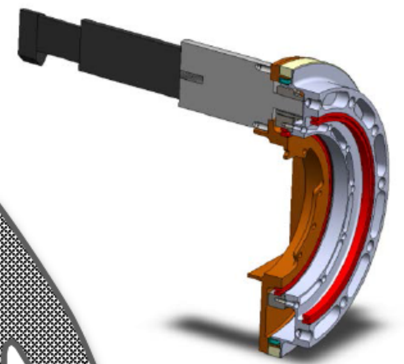
THEN WE DISCOVERED …

JPL Designs from 1970s

Axel Version 3 – Design

Design by Jaret Matthews





Wheel Performance - Obstacle Traversal

P. Abad-Manterola et al., “Wheel Design and Tension Analysis for the Tethered Axel Rover on Extreme Terrain,” 2009.

vs.

Mountain bike tires

~3” obstacles
(12% wheel diameter)

Grouser (paddle) wheels

~15” obstacles
(58% wheel diameter)

With a 5x increase in obstacle traversal performance, grouser wheels were selected for extreme terrain mobility, despite lower efficiency.

Wheel Performance Efficiency

Flat ground efficiency

Paddle

Max power ~200 W

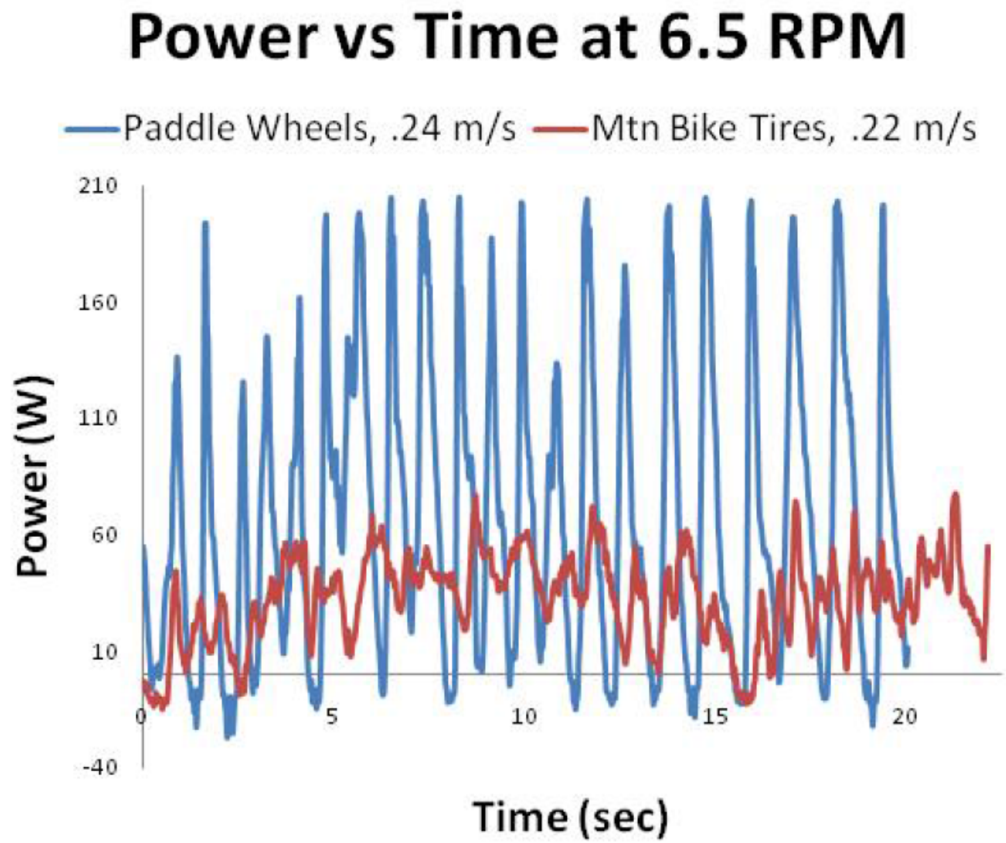
91 - 462 J/m

Mountain Bike

Max power ~75 W

34 – 259 J/m

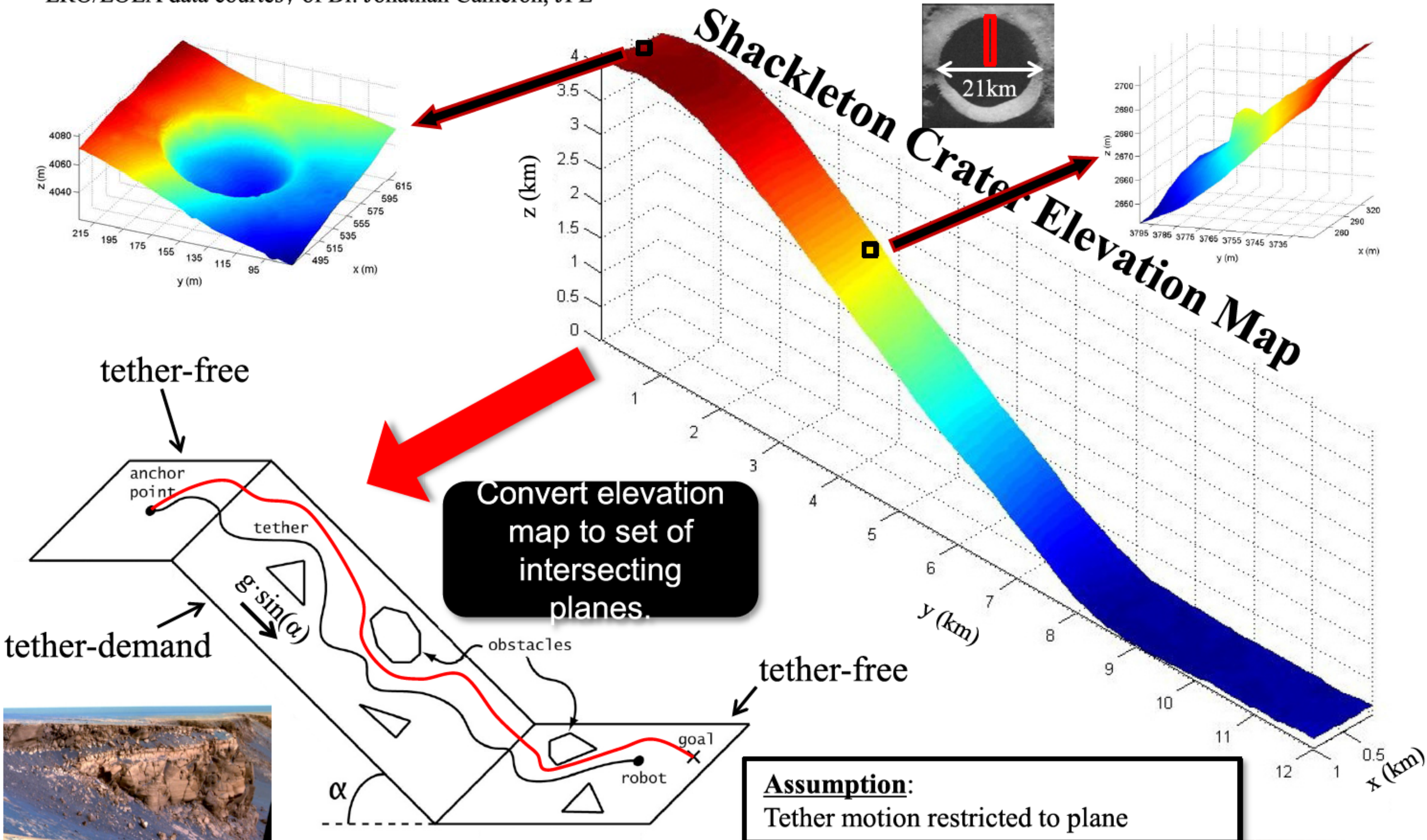
- 16 ft. long straight course
- 15 runs for each wheel type (3 runs for each of 5 speeds)



P. Abad-Manterola et al., “Wheel Design and Tension Analysis for the Tethered Axel Rover on Extreme Terrain,” 2009.

Tethered Motion Planning

LRO/LOLA data courtesy of Dr. Jonathan Cameron, JPL



Assumption:
Tether motion restricted to plane

FIELD TRIALS

Vulcan Trial

Steep slope test

Axel descended and ascended slopes ranging from 65° - 85°
Recurring slope lineae (RSL) appear during warm seasons

Thin-film Antenna Deployment

Concluding Thoughts

- Advancing mobility and autonomy would extend our exploration capabilities for future space missions
- Several recent discoveries were in ***extreme terrains***
- Some of the most interesting sites are currently inaccessible to state-of-the-art mobility platforms
- Extreme environments, communications constraints and space environment pose severe design challenges
- Space missions are expensive and opportunities quite limited
- However, new ideas and approaches, and a will to advance the art, we would overcome such challenges
- Autonomy would play a key role
- Prototyping and field-testing would be a critical

ACKNOWLEDGEMENTS

Acknowledgements

Axel Team

- Jaret Matthews
- Jack Morrison
- Pamela Conrad
- Robert Anderson
- Robert Peters
- Ben Solish
- Raymond Christian
- Jack Dunkle
- Summer students

Axel Caltech Team

- Prof. Joel Burdick
- Pablo Abad-Manterola
- Jeffrey Edlund
- Melissa Tanner
- Summer students

SCIP Team

- Mihail Pivtoraiko
- Michael Fleder

Visual Tracking Team

- Won Soo Kim
- Richard Madison
- Max Bajracharya

CLARAty Team

- JPL Team
- Carnegie Mellon Team (Reid Simmons)
- NASA Ames Team (Anne Wright)

Acknowledgements

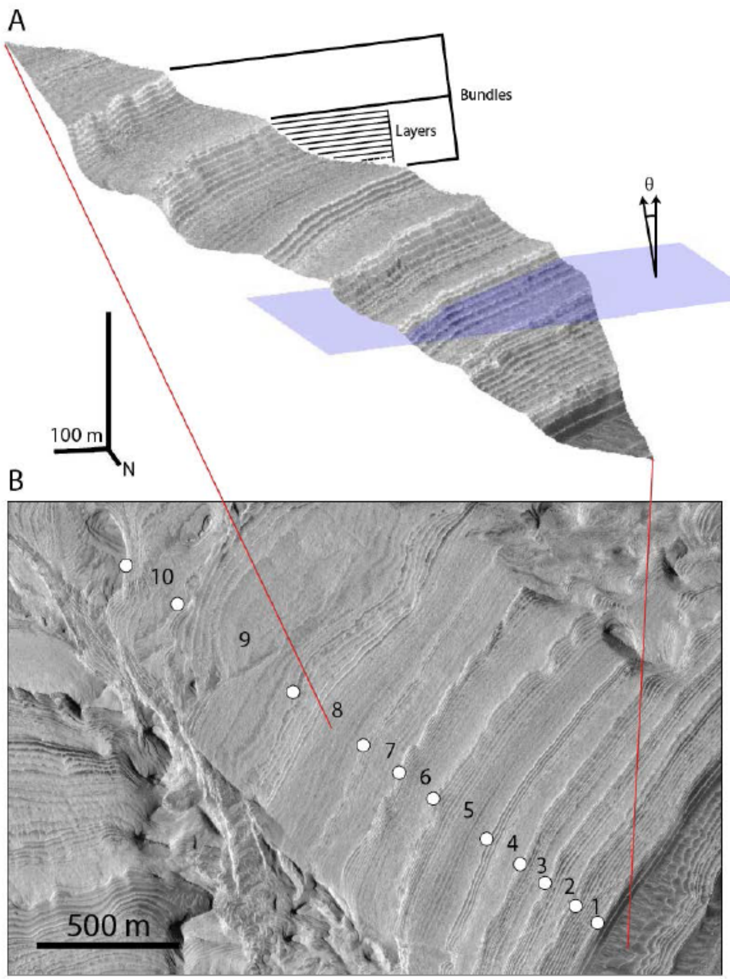
- **JPL's Office of Chief Scientist/Technologist**
  - Research and Technology Development Program (2010-2011)
- **Keck Institute for Space Studies**
  - Extreme Terrain Exploration (2009)
- **Caltech's and NSF's student support**
- **JPL's Solar System Mission Formulation Office**
  - MIRANDA mission study (2009-2010)
  - xPRM mission study (2010)
- **NASA's Mars Technology Program** (2007)
- **JPL's Solar System Exploration Program** (2006)
- **JPL's Education Office**
  - Space Grant Program (2003-2006)
- **JPL's Advanced Concepts Program** (2000)

THANK YOU

QUESTIONS?

Space and Terrestrial Applications

Mars



Credit: Kevin W. Lewis, et.al. "Quasi-Periodic Bedding in the Sedimentary Rock Record of Mars," Science 5 December 2008

Goldstrike Mine, Nevada

Future Work

- Reduce mass and volume
- Complete DuAxel/Axel interface trades
- Mature anchoring/de-anchoring
- Optimize wheel designs
- Optimize energy
- Investigate extend operations
- Acquire cores from slopes
- Develop autonomy
  - Motion planning
  - Undocking and redocking
  - Traverses to designated targets
  - Tether control

Credit: Aaron Parness (PI)

Jet Propulsion Laboratory
California Institute of Technology

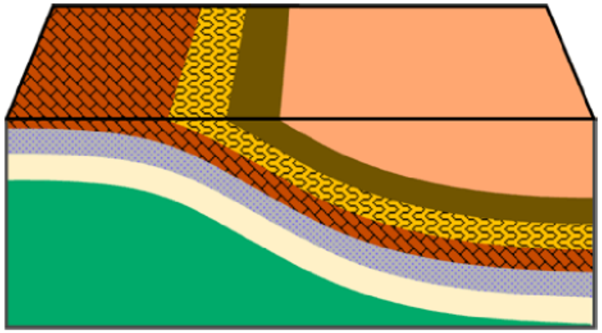
MER Driving Speeds

- Directed ("blind"): 120 m/hr. Gear ratios limit top mechanical speed to 5 cm/sec (180 m/hr), but nominally no more than 3.7 cm/sec (133 m/hr, less cool-off/re-steer periods).
- Hazard avoidance ("AutoNav"): 10-35 m/hr. Rover moves in 50 cm steps, but only images every 1.5 m (Spirit) or 2 m (Opportunity) in benign terrain. When obstacles are nearby, imaging occurs at each step.
- Visual Odometry ("VisOdom"): 10 m/hr. Desire is to have 60% image overlap; in NAVCAMs pointed nearby, that limits motions to at most 60cm forward or 18 degrees turning in place.

Exploring Extreme Terrain

- **What do we mean by *extreme* terrain?**
  - Terrain that is inaccessible to and not traversable by state-of-the-art planetary robots (e.g. Valles Marineris, steep exposed strata, crater floors, high-slip or high-sink areas). Such terrains pose excessive risk for current missions

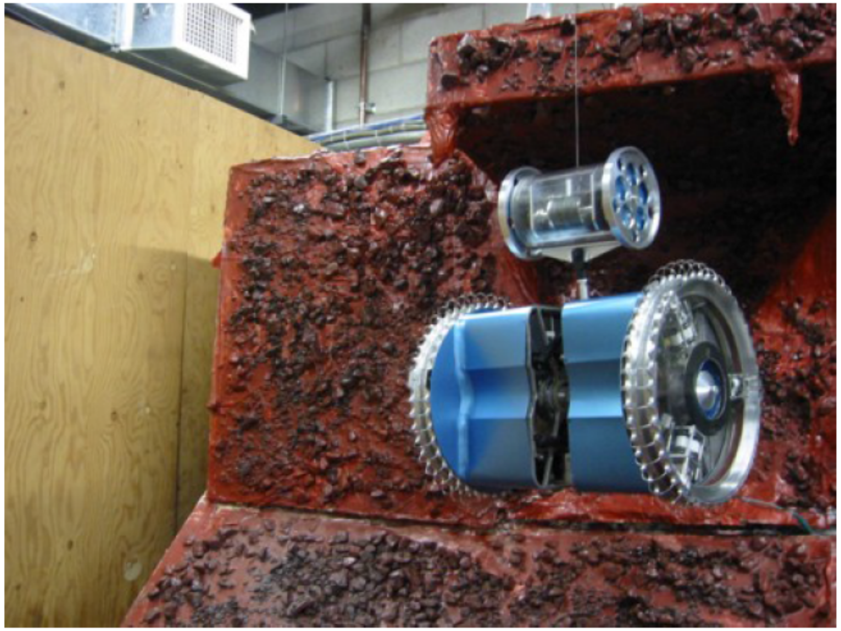
- **Why *extreme* terrain?**
  - Anticipation that extreme terrain may lead to a wealth of scientific information about planetary bodies
    - Provides direct access to and enables in-situ measurements on stratigraphic layers
    - Enables exploration of the craters interiors (transects and crater floors)
    - Enables access to potential caves

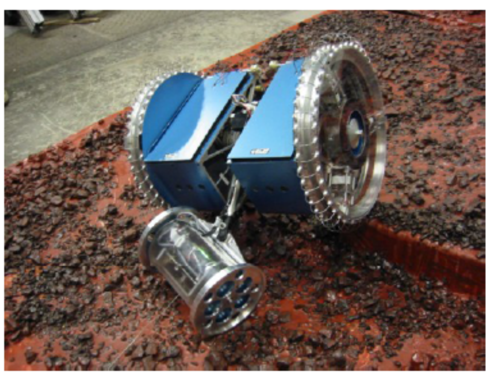


Other Axel-like Robots

Scout from ReConn
- Successful commercial application
- Un-tethered reconnaissance robot
- Can be thrown into buildings through windows
- Uses magnetic wheels to climb vertical walls

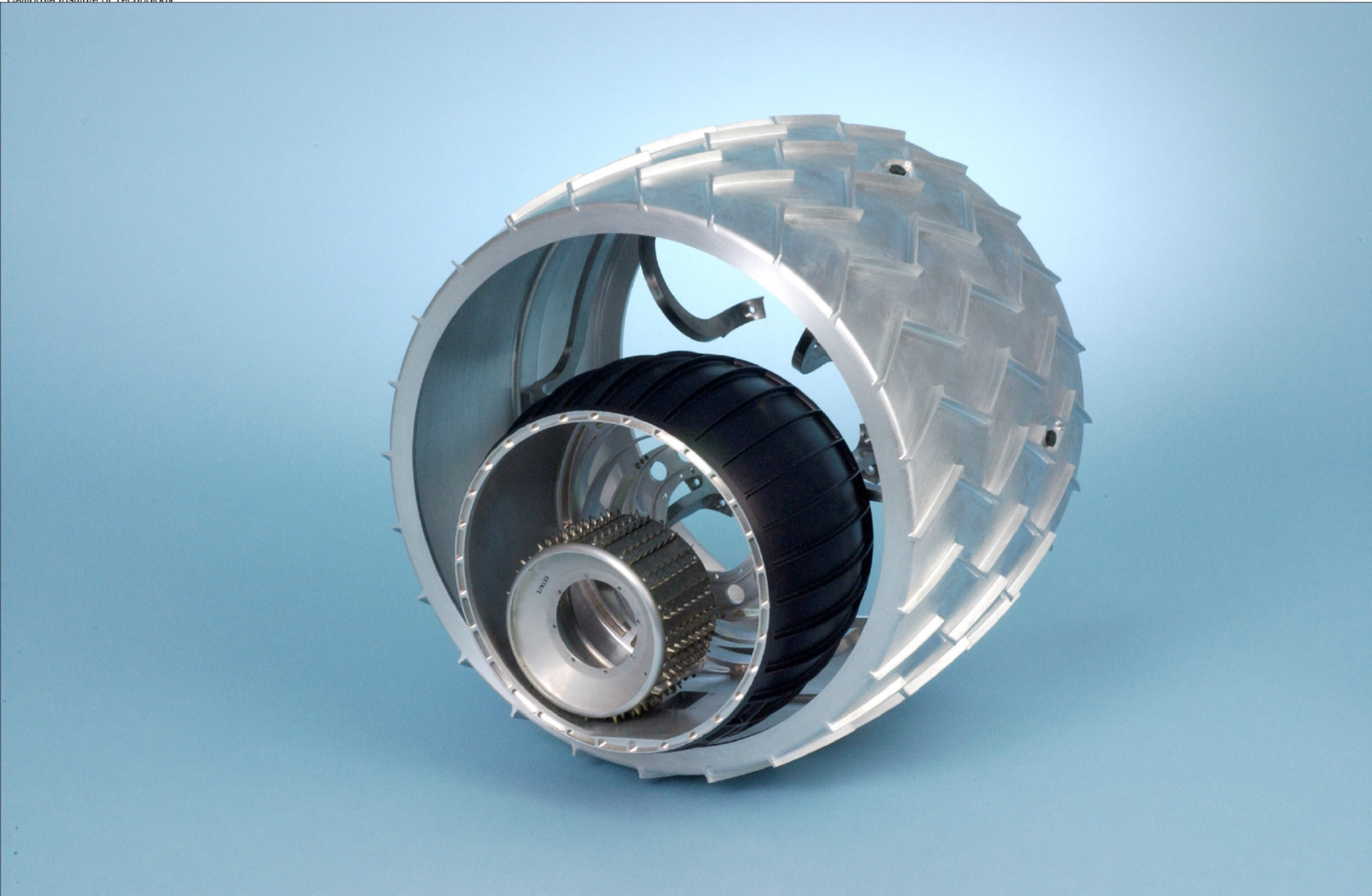
Other Axel-like Robots

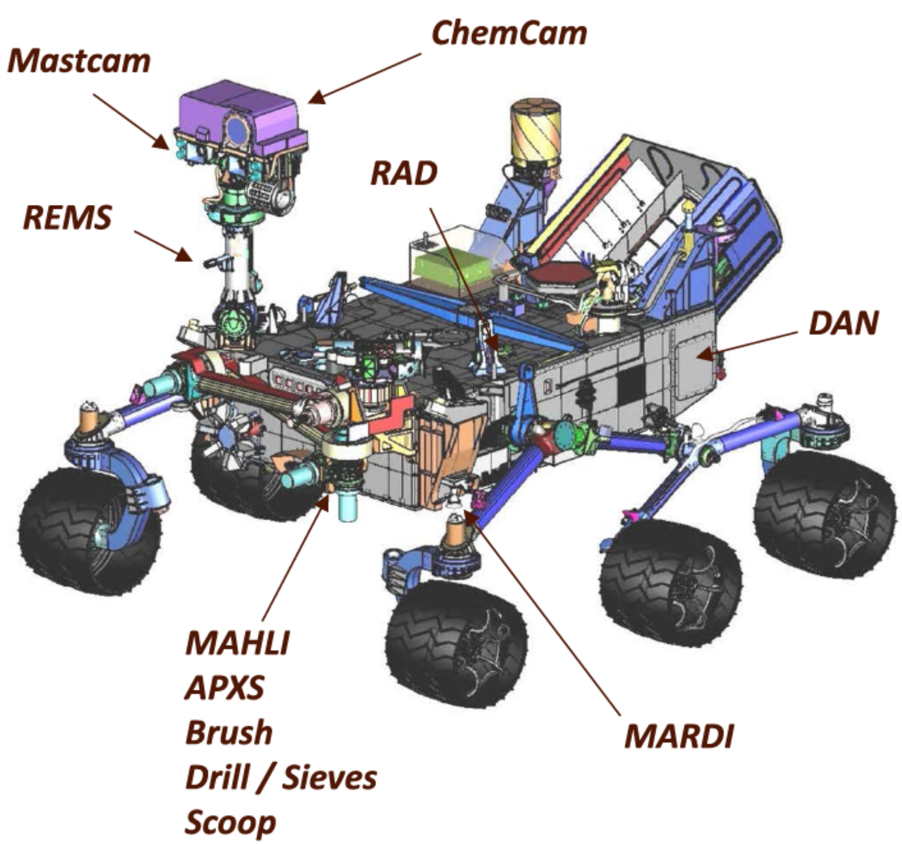




2005 Cezar Rover – U. of Bremen, Germany
Won European Space Agency competition

2003 Canadian Space Agency - Extreme terrain robot
Independently developed by Sherbrooke University





Wheel Base:	**2.8 m**
Height of Deck:	**1.1 m**
Ground Clearance:	**0.66 m**
Height of Mast:	**2.2 m**

REMOTE SENSING

Mastcam (M. Malin, MSSS) - Color and telephoto imaging, video, atmospheric opacity

ChemCam (R. Wiens, LANL/CNES) – Chemical composition; remote micro-imaging

CONTACT INSTRUMENTS (ARM)

MAHLI (K. Edgett, MSSS) – Hand-lens color imaging

APXS (R. Gellert, U. Guelph, Canada) - Chemical composition

ANALYTICAL LABORATORY (ROVER BODY)

SAM (P. Mahaffy, GSFC/CNES) - Chemical and isotopic composition, including organics

CheMin (D. Blake, ARC) - Mineralogy

ENVIRONMENTAL CHARACTERIZATION

MARDI (M. Malin, MSSS) - Descent imaging

REMS (J. Gómez-Elvira, CAB, Spain) - Meteorology / UV

RAD (D. Hassler, SwRI) - High-energy radiation

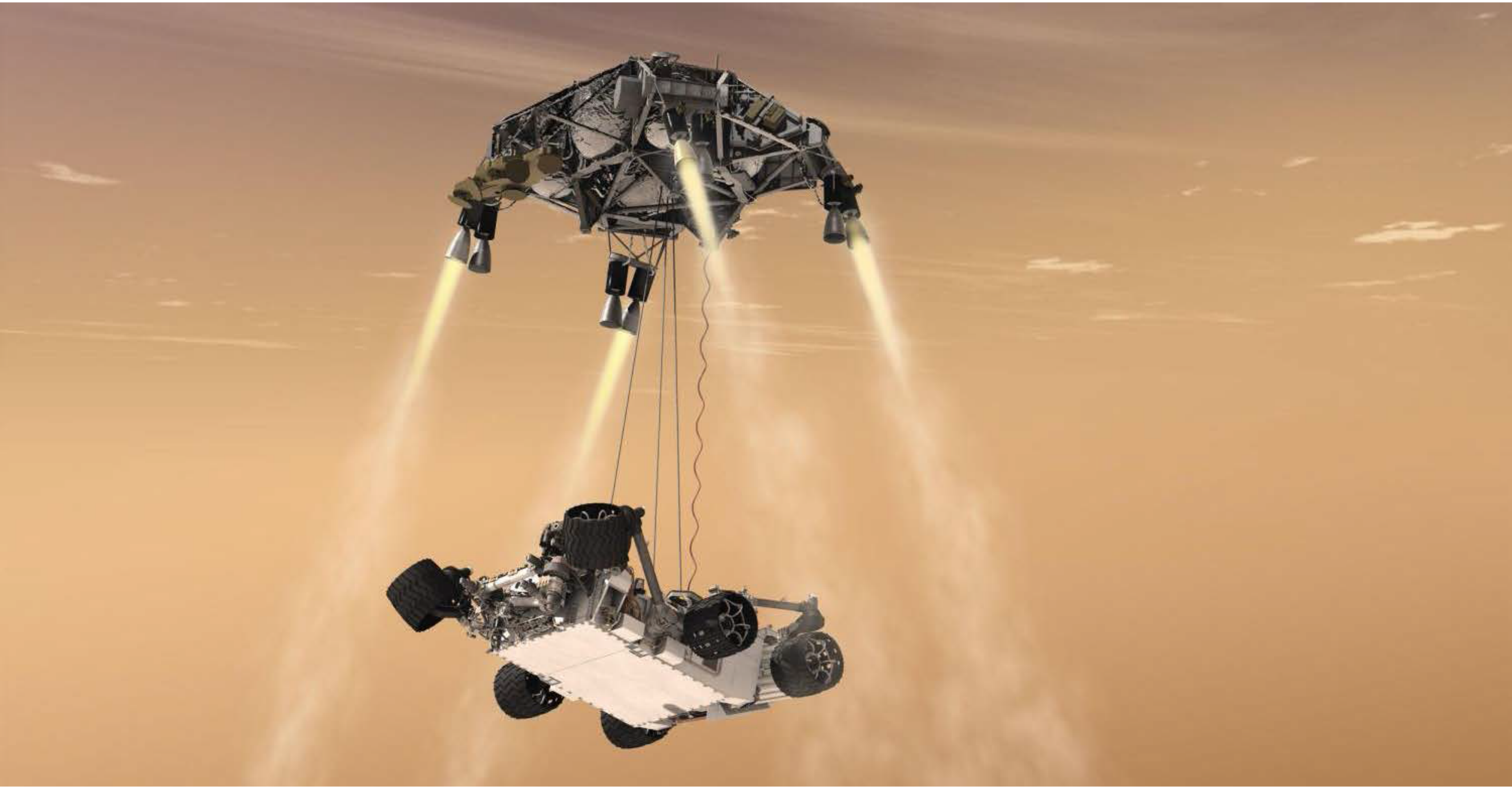
DAN (I. Mitrofanov, IKI, Russia) - Subsurface hydrogen

Science Goals

MSL's primary scientific goal is to explore a landing site as a potential habitat for life, and assess its potential for preservation of biosignatures

Objectives include:

- Assessing the biological potential of the site by investigating organic compounds, other relevant elements, and biomarkers
- Characterizing geology and geochemistry, including chemical, mineralogical, and isotopic composition, and geological processes
- Investigating the role of water, atmospheric evolution, and modern weather/climate
- Characterizing the spectrum of surface radiation



Artist's Concept. NASA/JPL-Caltech