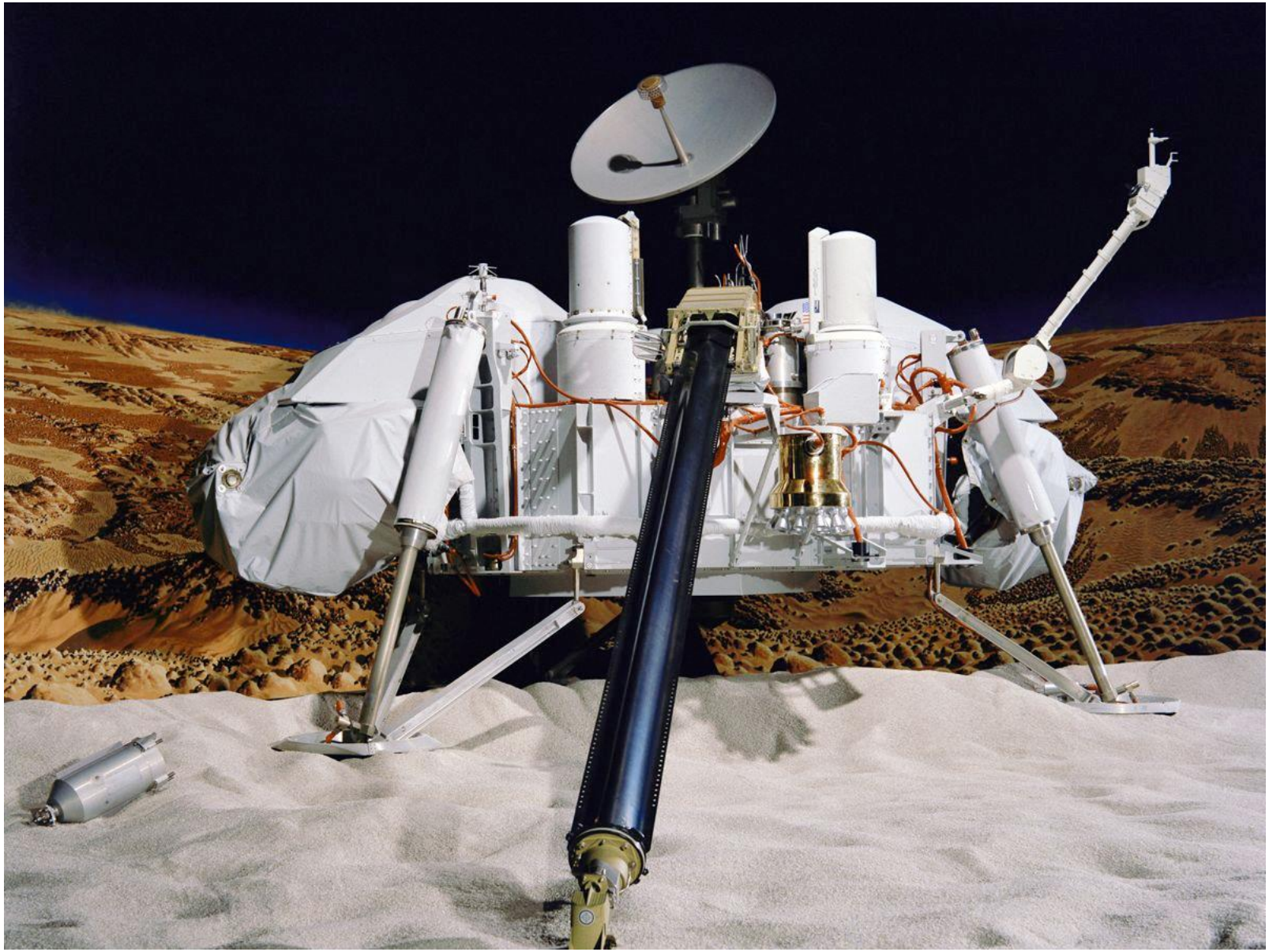
The Guidance, Navigation, and Control Challenges of Landing on Mars and Europa

The 2018 American Control Conference
Milwaukee, Wisconsin
June 27, 2018

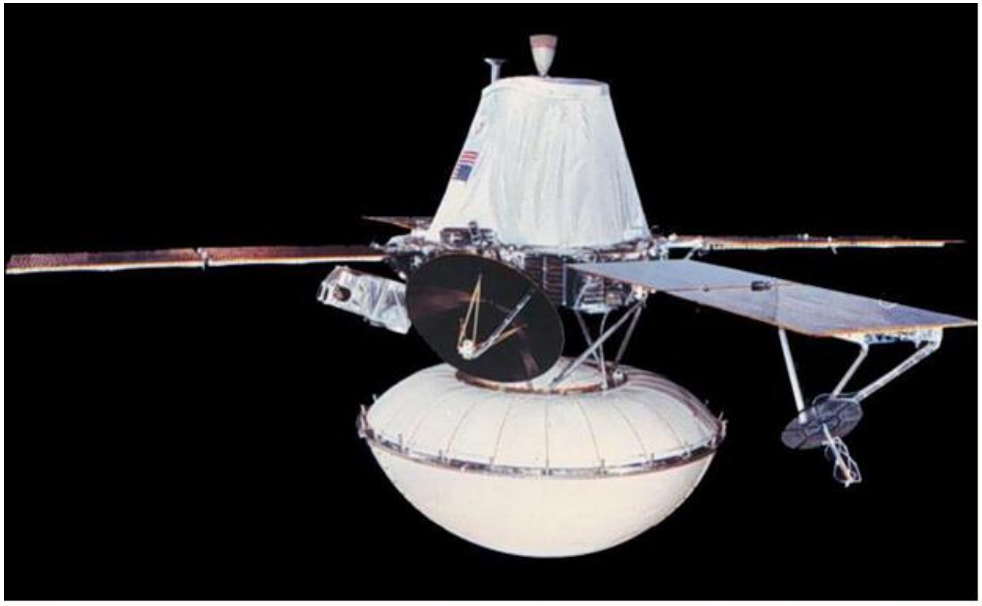
A. Miguel San Martin

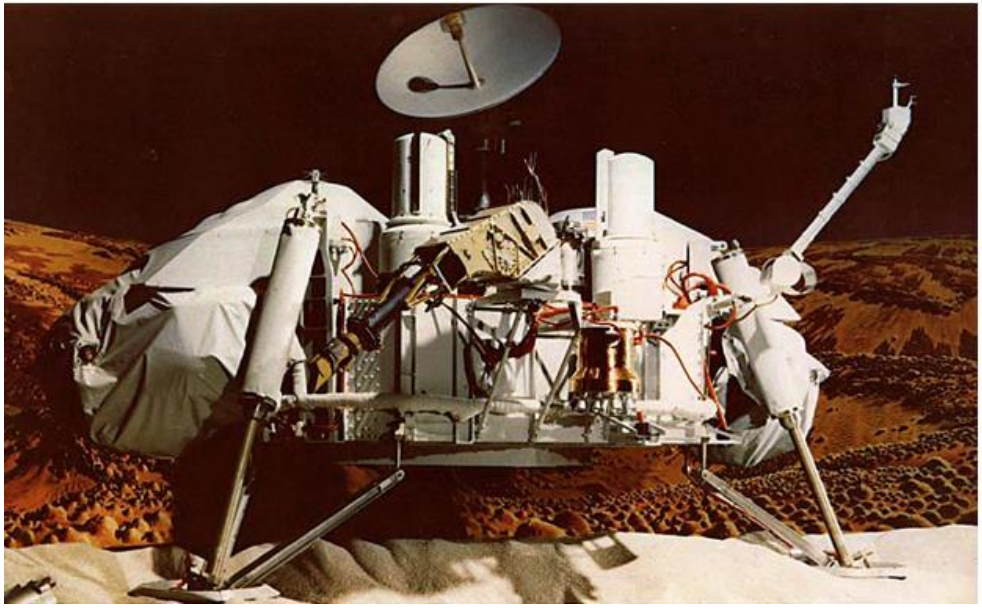
Jet Propulsion Laboratory
California Institute of Technology

Viking I & II (1976)



Viking I & II (1976)



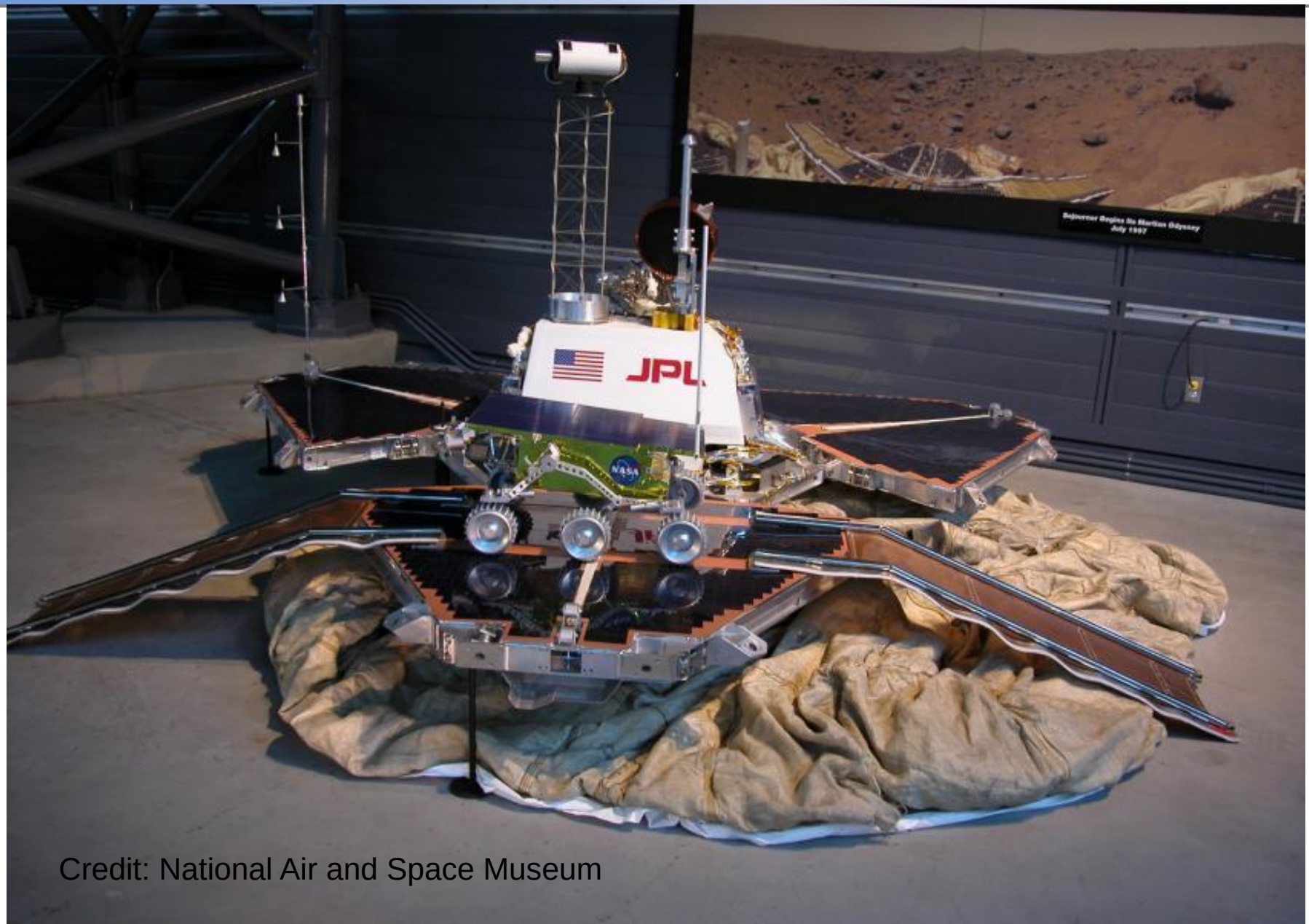


JPL
Jet Propulsion Laboratory
California Institute of Technology

Viking I and Big Joe

NASA

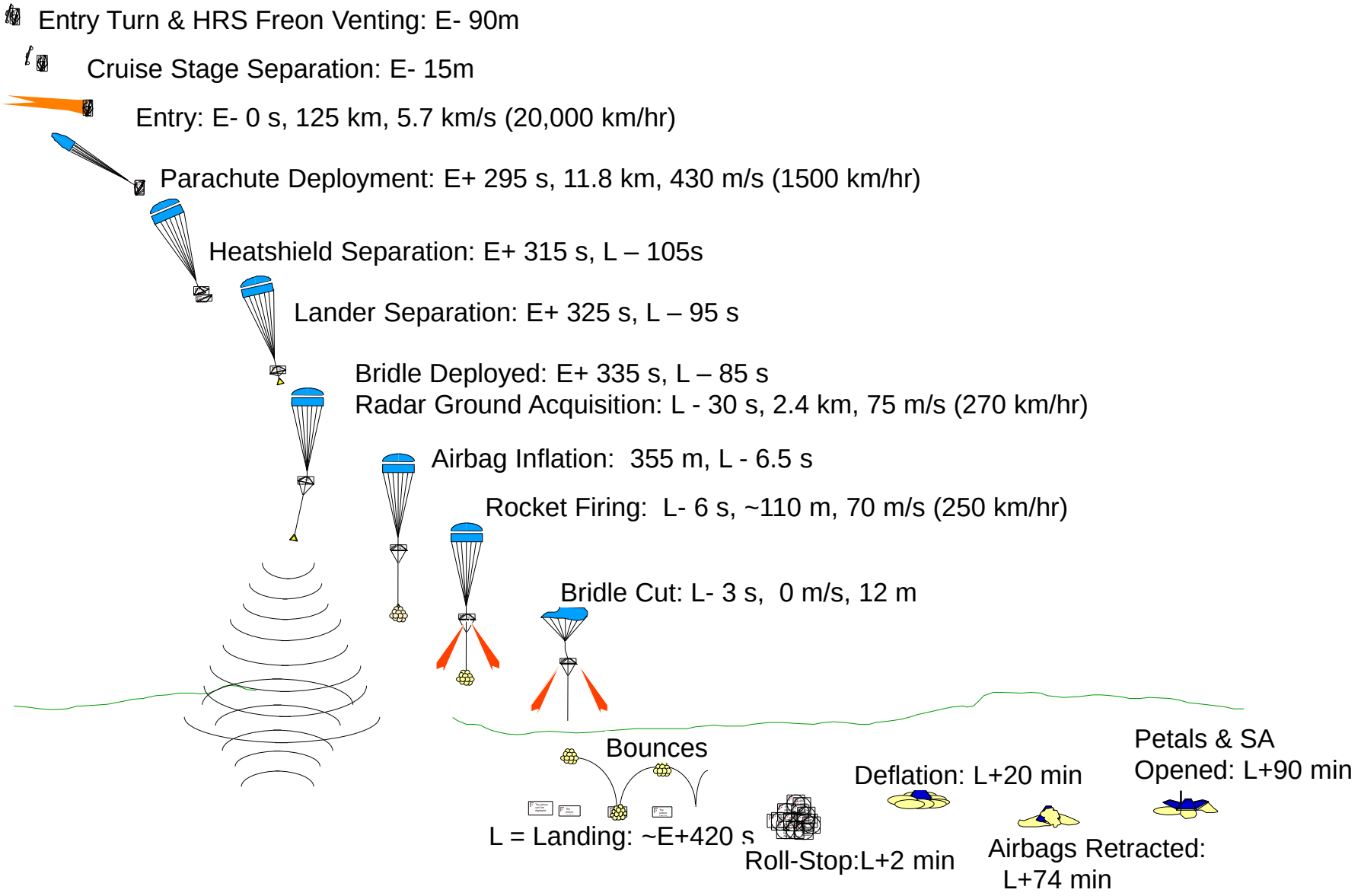
Mars Pathfinder (1997)



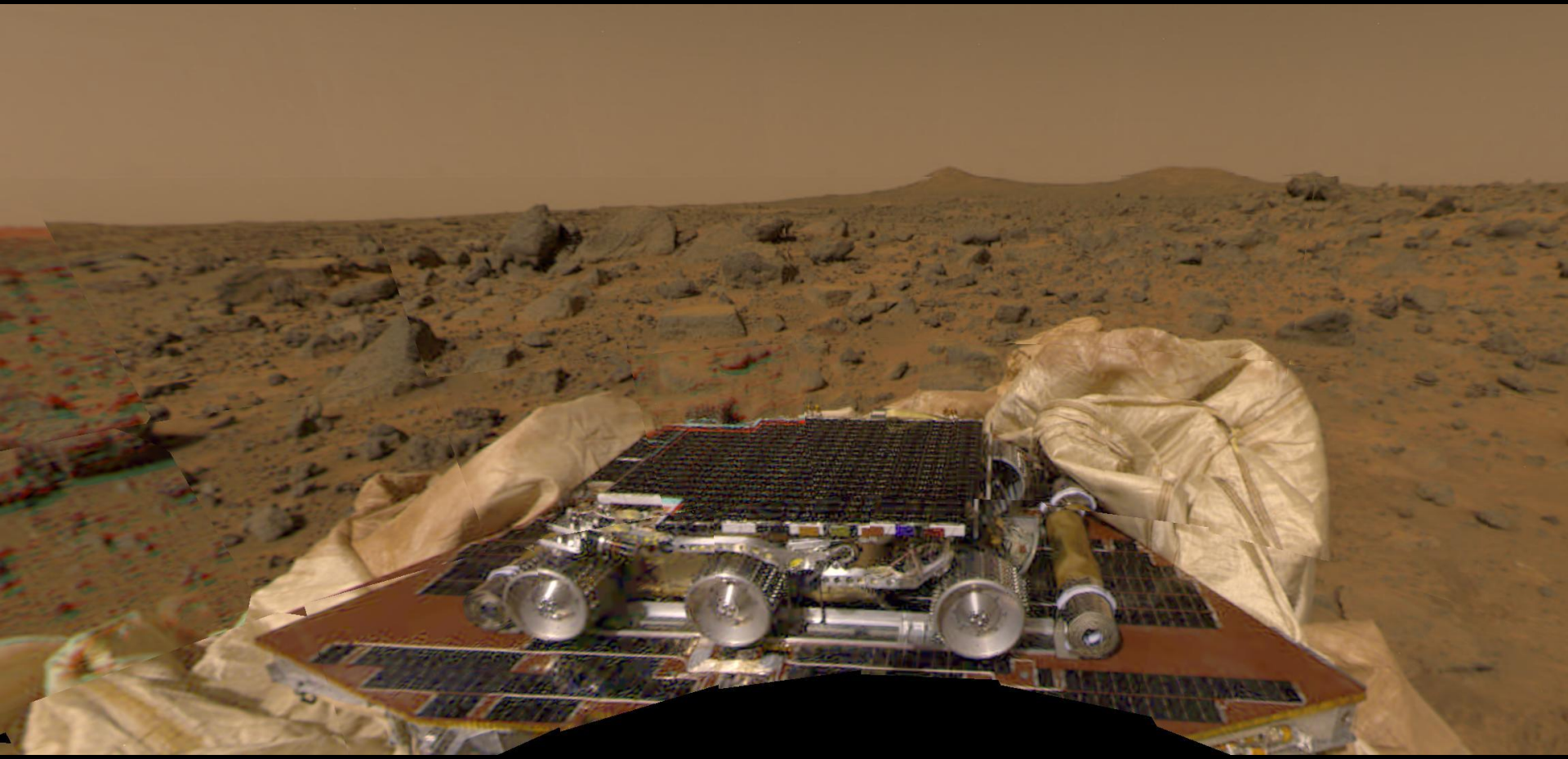
Credit: National Air and Space Museum

Mars Pathfinder (1997)

Entry, Descent & Landing Timeline

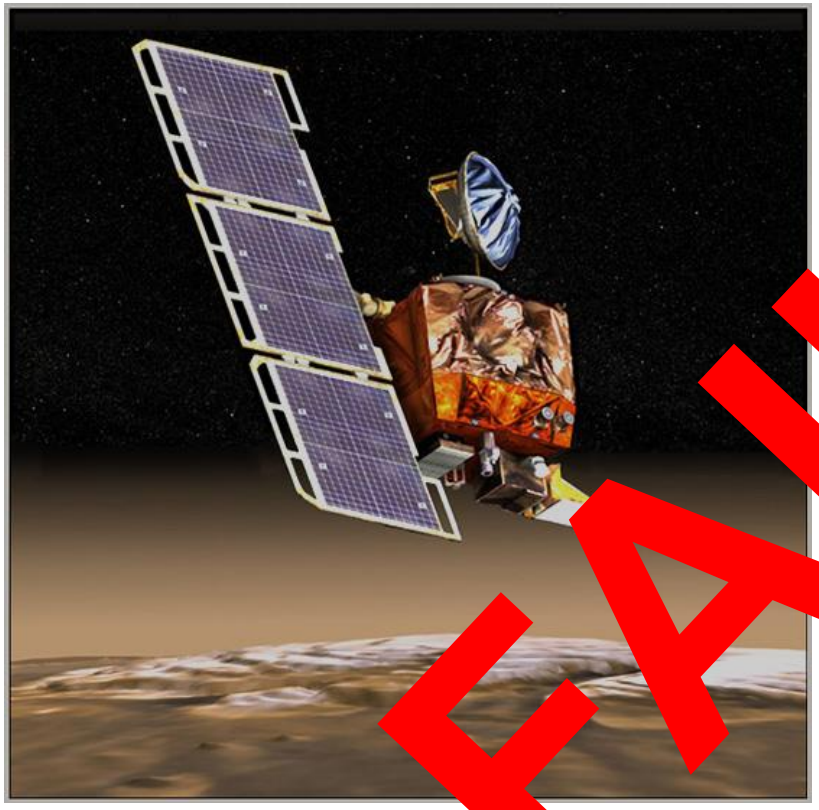


July 4, 1997



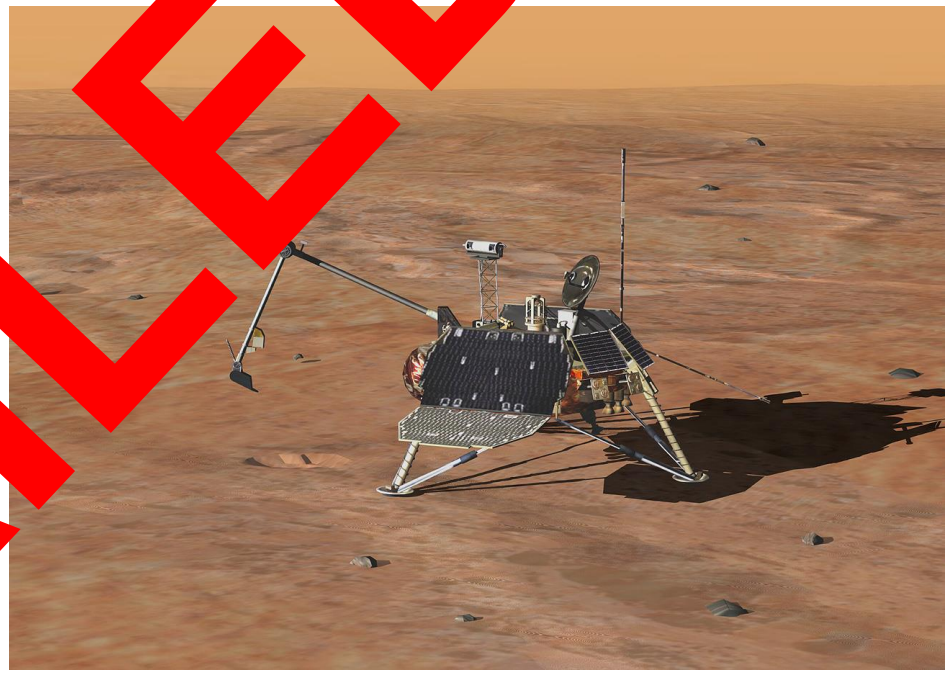
Sojourner Rover and Yogi

Mars Climate Orbiter



September 23, 1999

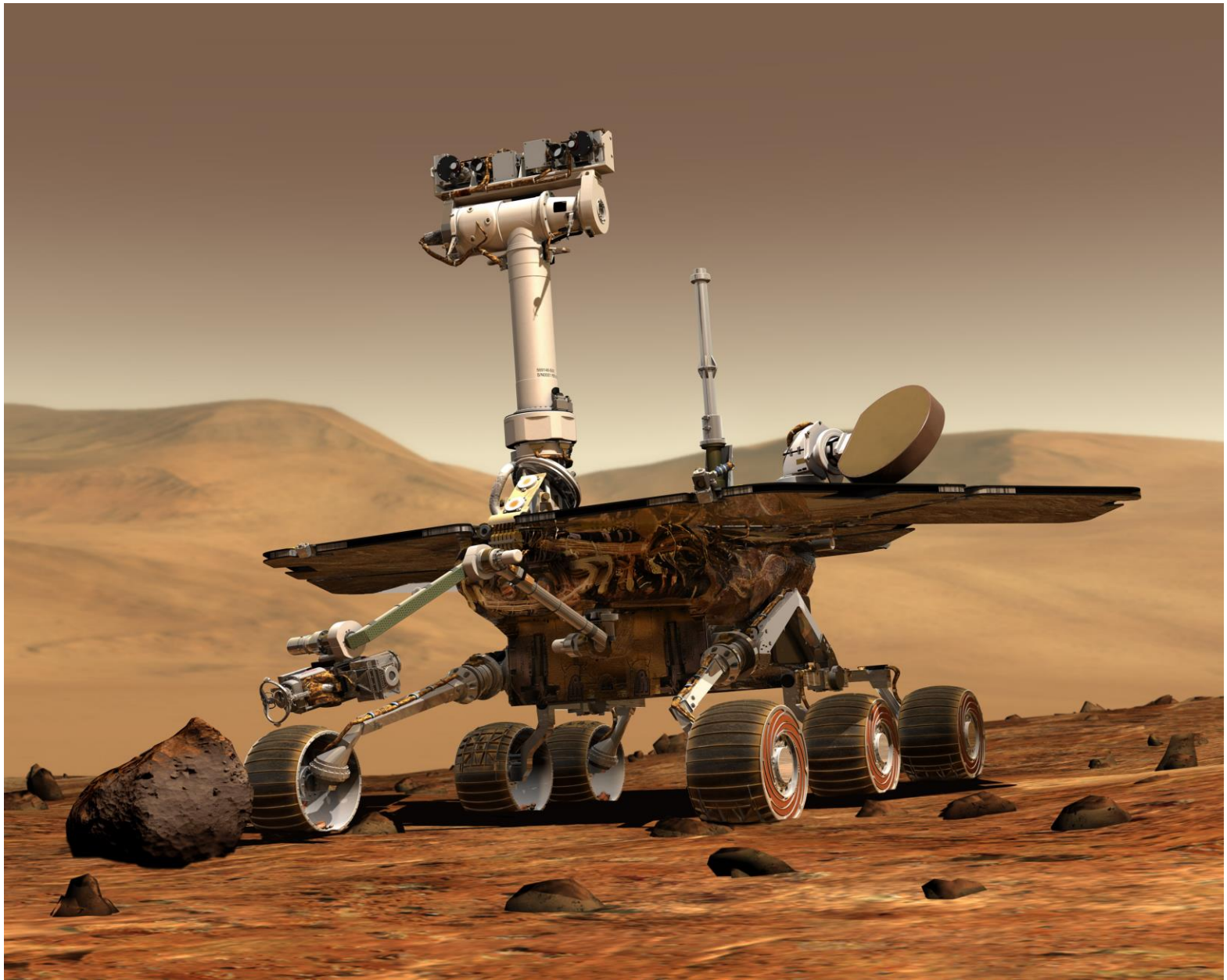
Mars Polar Lander

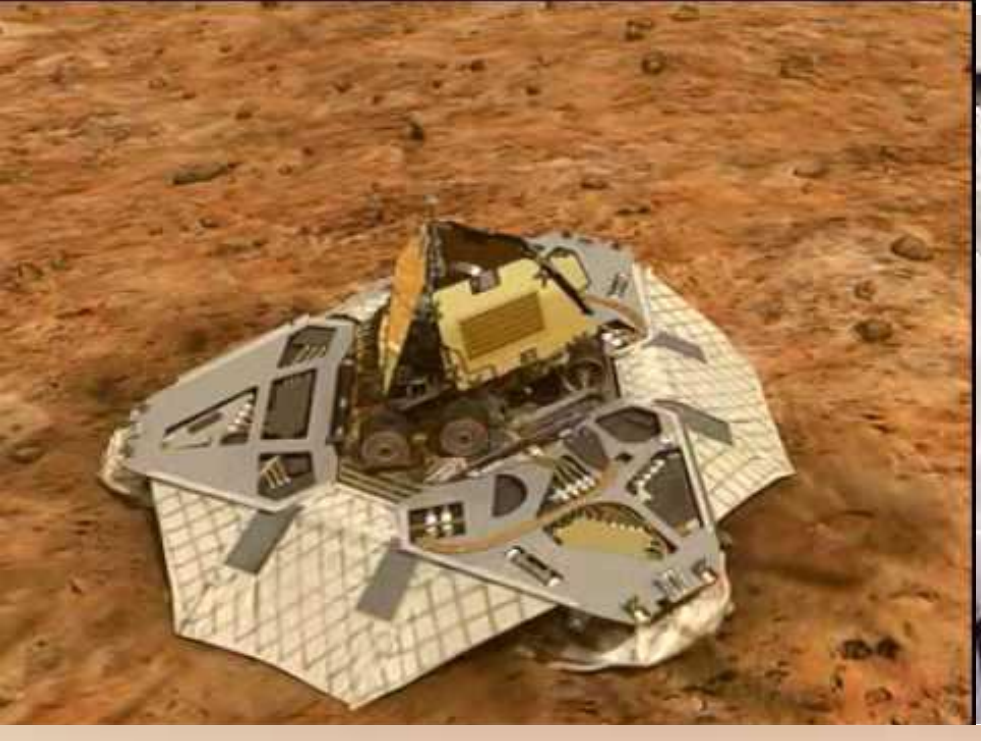


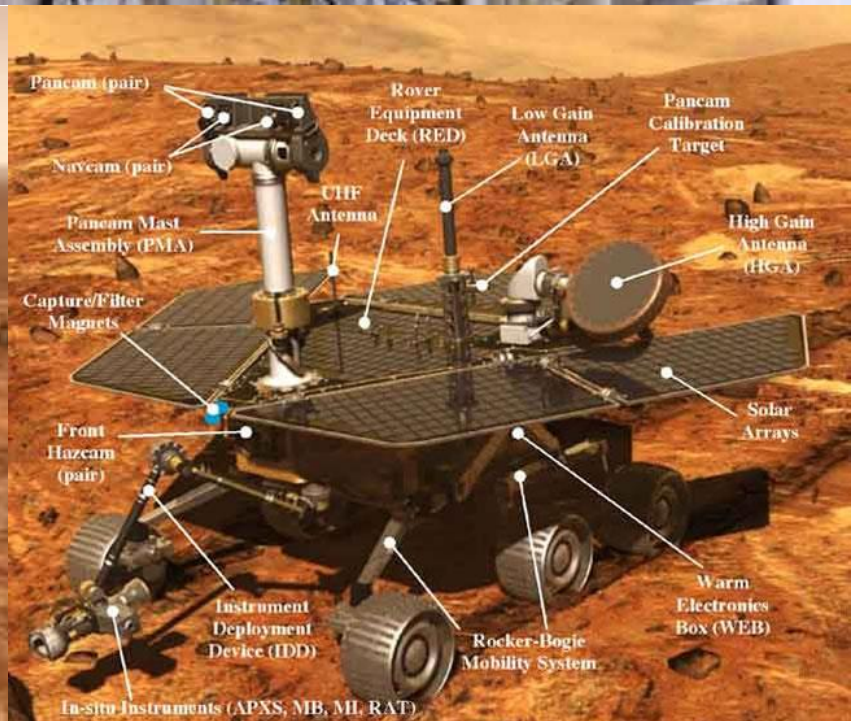
December 23, 1999

FAILED

Spirit/Opportunity Rovers (2004)

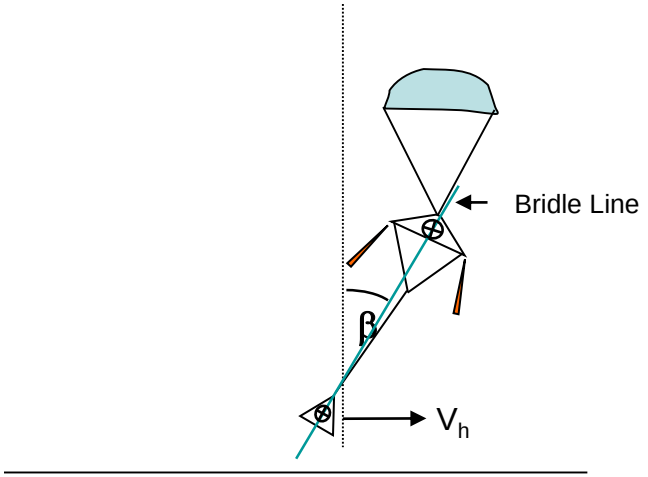





Pancam (pair)
Navcam (pair)
Rover Equipment Deck (RED)
Low Gain Antenna (LGA)
Pancam Calibration Target
UHF Antenna
Pancam Mast Assembly (PMA)
High Gain Antenna (HGA)
Capture/Filter Magnets
Solar Arrays
Front Hazcam (pair)
Warm Electronics Box (WEB)
Instrument Deployment Device (IDD)
Rocker-Bogie Mobility System
In-situ Instruments (APXS, MB, MI, RAT)

Sources of Horizontal Velocity

- Definitions:
  - *Initial Horizontal Velocity*
    - Steady State winds
    - Parachute instability (I.e. trim angle) induced
  - *RAD Induced Horizontal Velocity*
    - Wind Shear
    - Parachute instability
    - Uncontrolled
      - RAD rockets thrust mismatch induced
      - RAD rockets misalignment induced
      - Backshell c.o.m. offset induced
      - Bridal confluence point offset induced



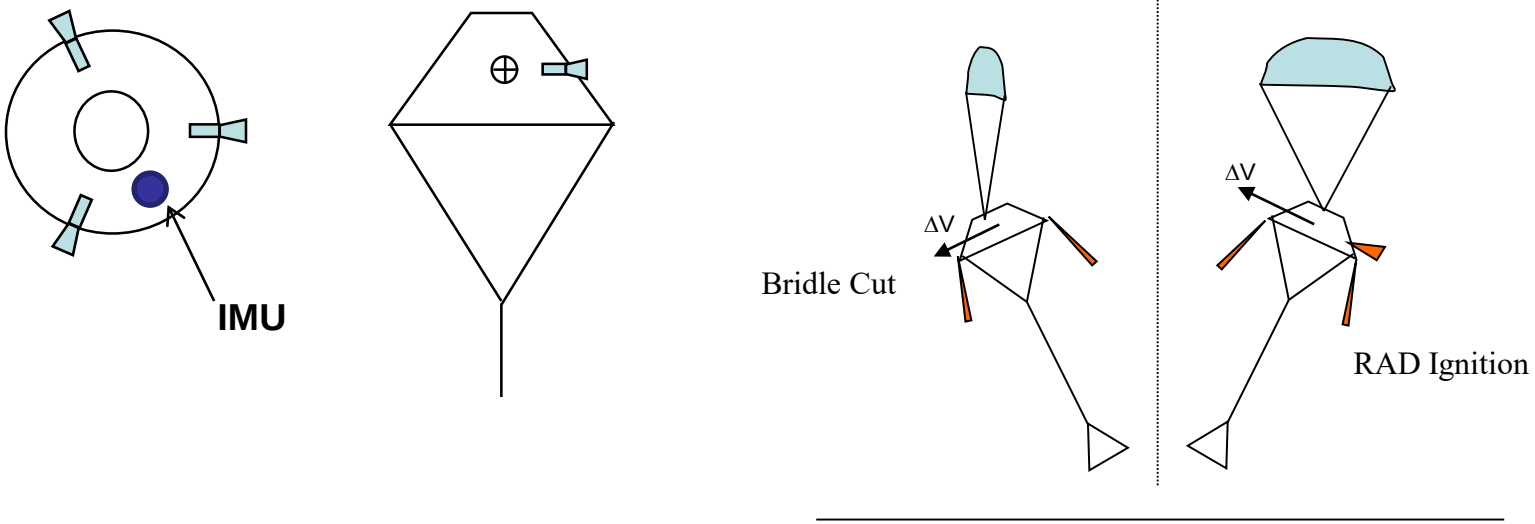
Initial Horizontal Velocity — RAD Induced Horizontal Velocity

$$V_h(t_{bc}) = V_h(t_{RAD}) + \int F_{RAD}/m * \sin(\beta)\, dt$$

- Example:
  - a 20 degrees Bridle Angle angle results in an horizontal velocity of 29 m/s

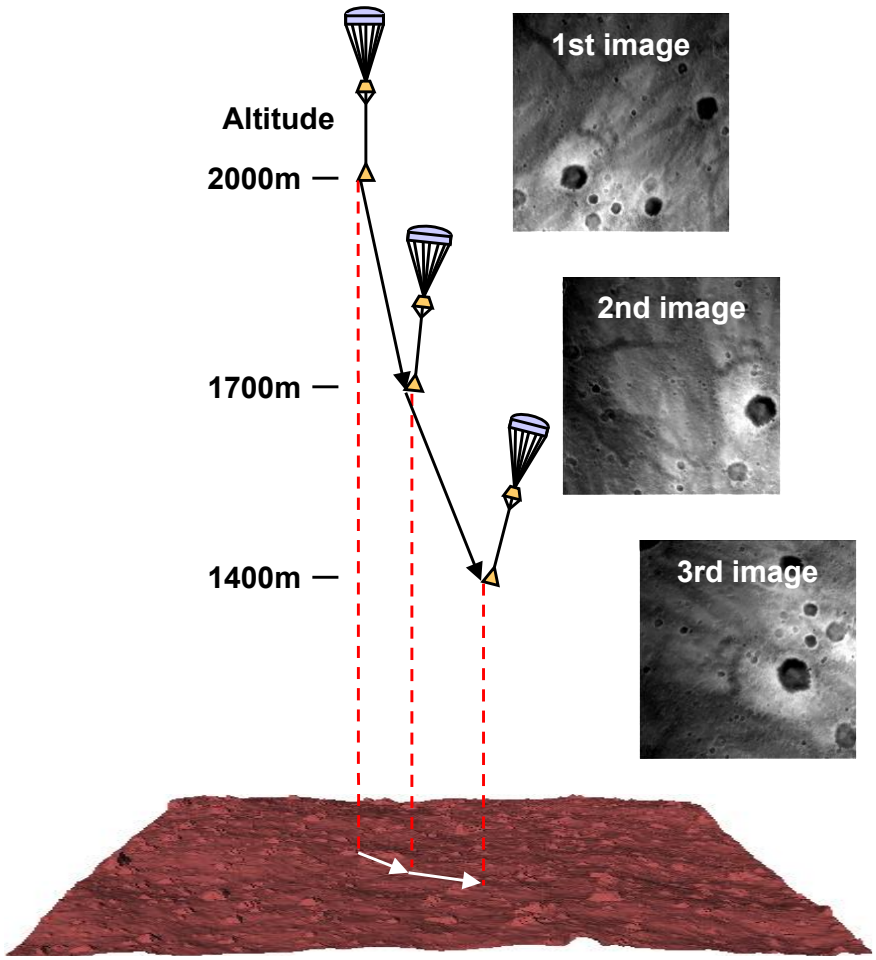
Transverse Impulse Rocket System (TIRS)

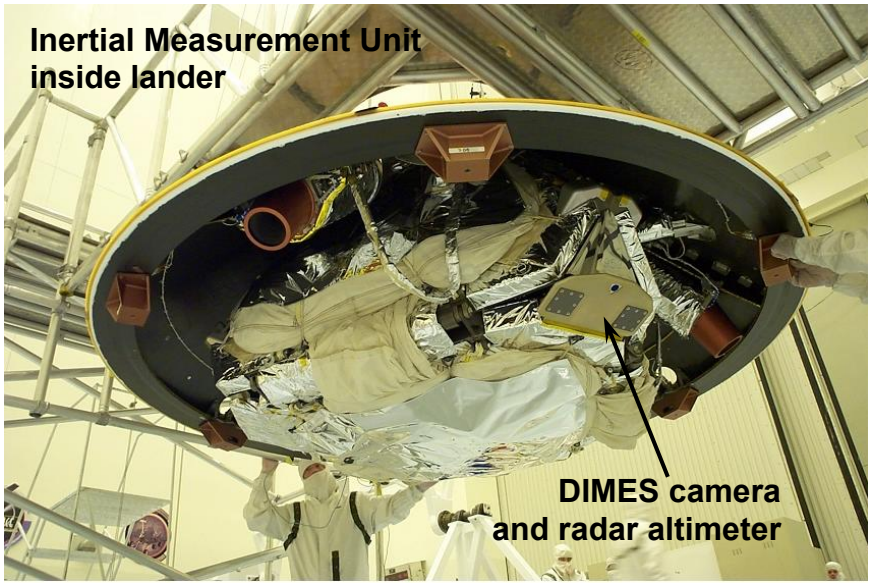
- Add three small rockets aimed at the backshell c.o.m. to impart impulsively a transverse delta-V to the backshell in order to reduce the average off-nadir angle during RAD firing.
  - Transverse Impulse Rocket System (TIRS)
  - Backshell deltaV = 5 m/sec
    - 40 degrees bridle angle correction in 3.3 sec of RAD firing
  - TIRS burn duration < 0.5 seconds



Descent Image Motion Estimation System (DIMES)

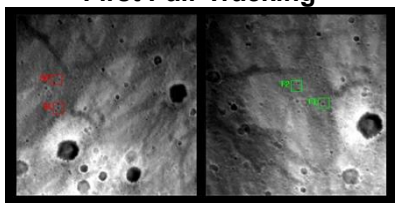
DIMES SCENARIO



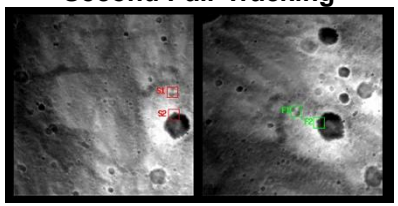


DIMES RESULT

First Pair Tracking

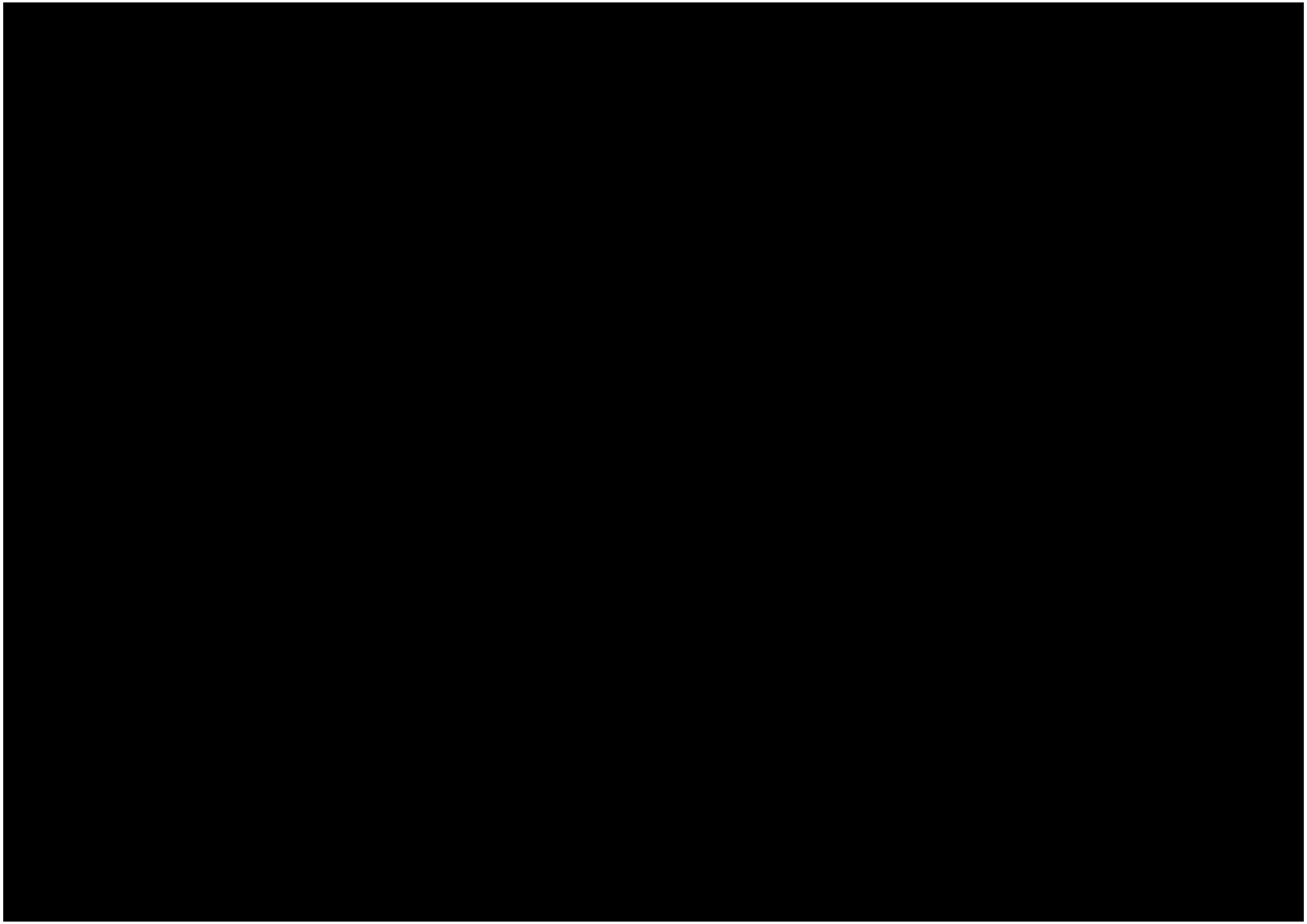


Second Pair Tracking

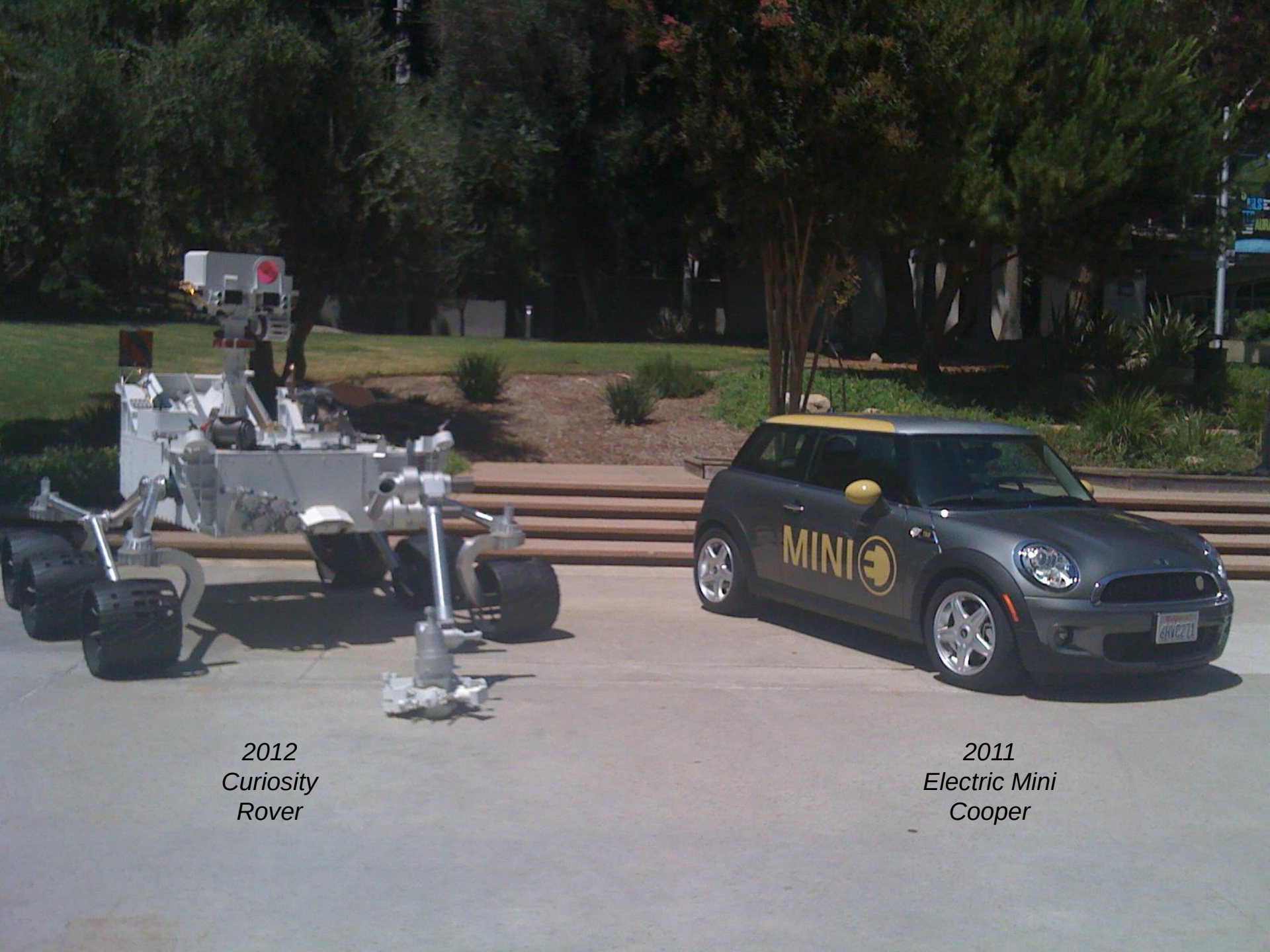


MER-A/Spirit, Gusev Crater, January 4th, 2004

Spirit Landing in January 2004

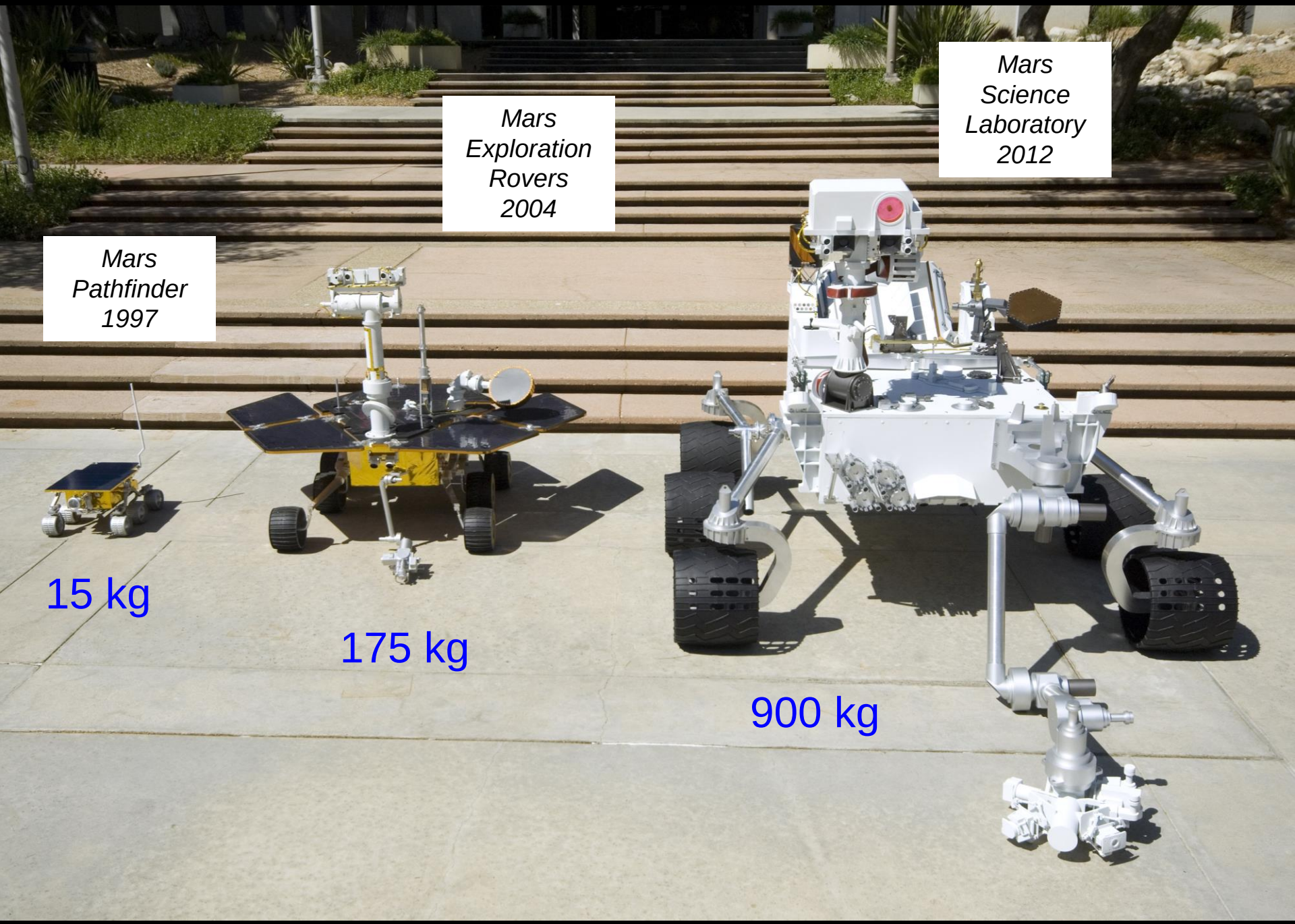


Rover Egress

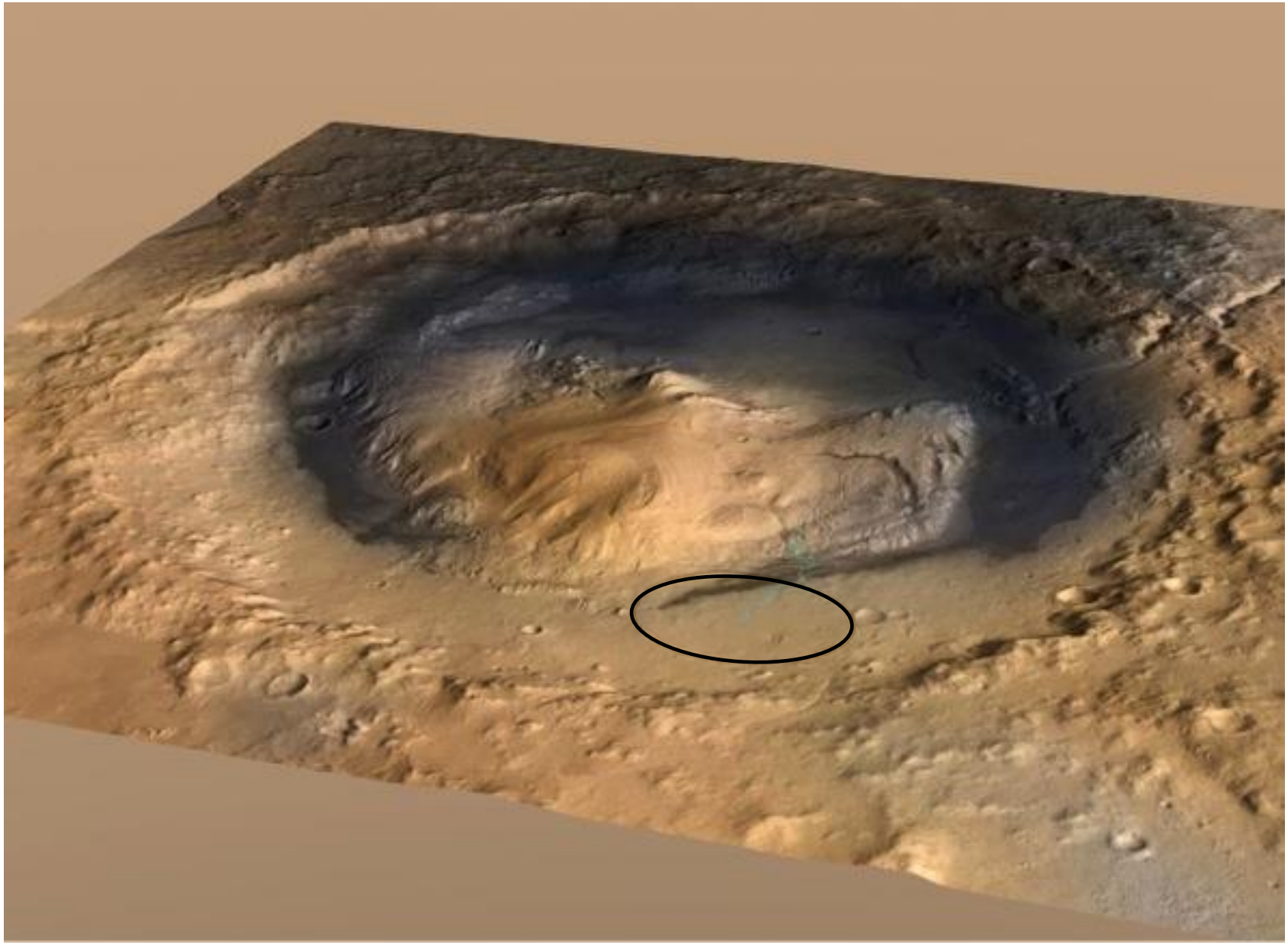


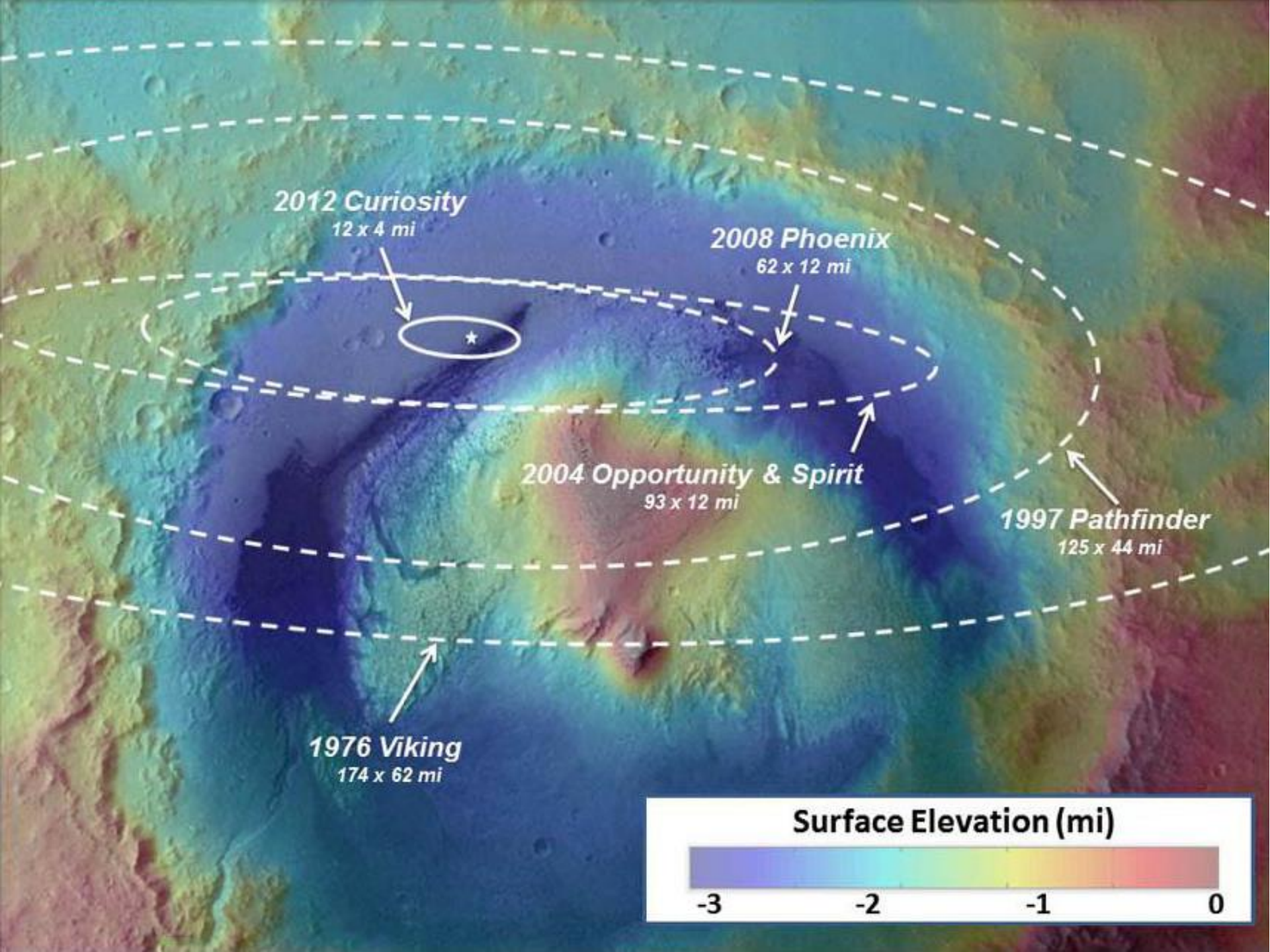
2012
Curiosity
Rover

2011
Electric Mini
Cooper


Mars Pathfinder 1997
Mars Exploration Rovers 2004
Mars Science Laboratory 2012
15 kg
175 kg
900 kg

MSL/Curiosity Landing Ellipse in Gale Crater




2012 Curiosity
12 x 4 mi
2008 Phoenix
62 x 12 mi
2004 Opportunity & Spirit
93 x 12 mi
1997 Pathfinder
125 x 44 mi
1976 Viking
174 x 62 mi
Surface Elevation (mi)
-3
-2
-1
0

Entry, Descent, and Landing Phases

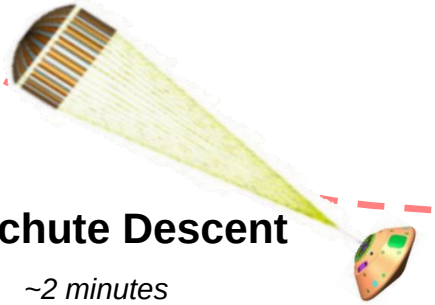
The 7 Minutes of Terror

20,000 km/h (E = 100%)
125 km

Entry

~4 minutes

1,500 km/h (E = 1%)
10 km



Parachute Descent

~2 minutes

Powered Descent

300 km/h (E = 0.02%)
1.8 km

Landing

~1 minute

Touchdown

3 km/h (E = 2 10^{-6}%)

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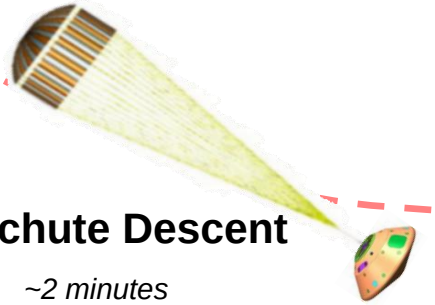

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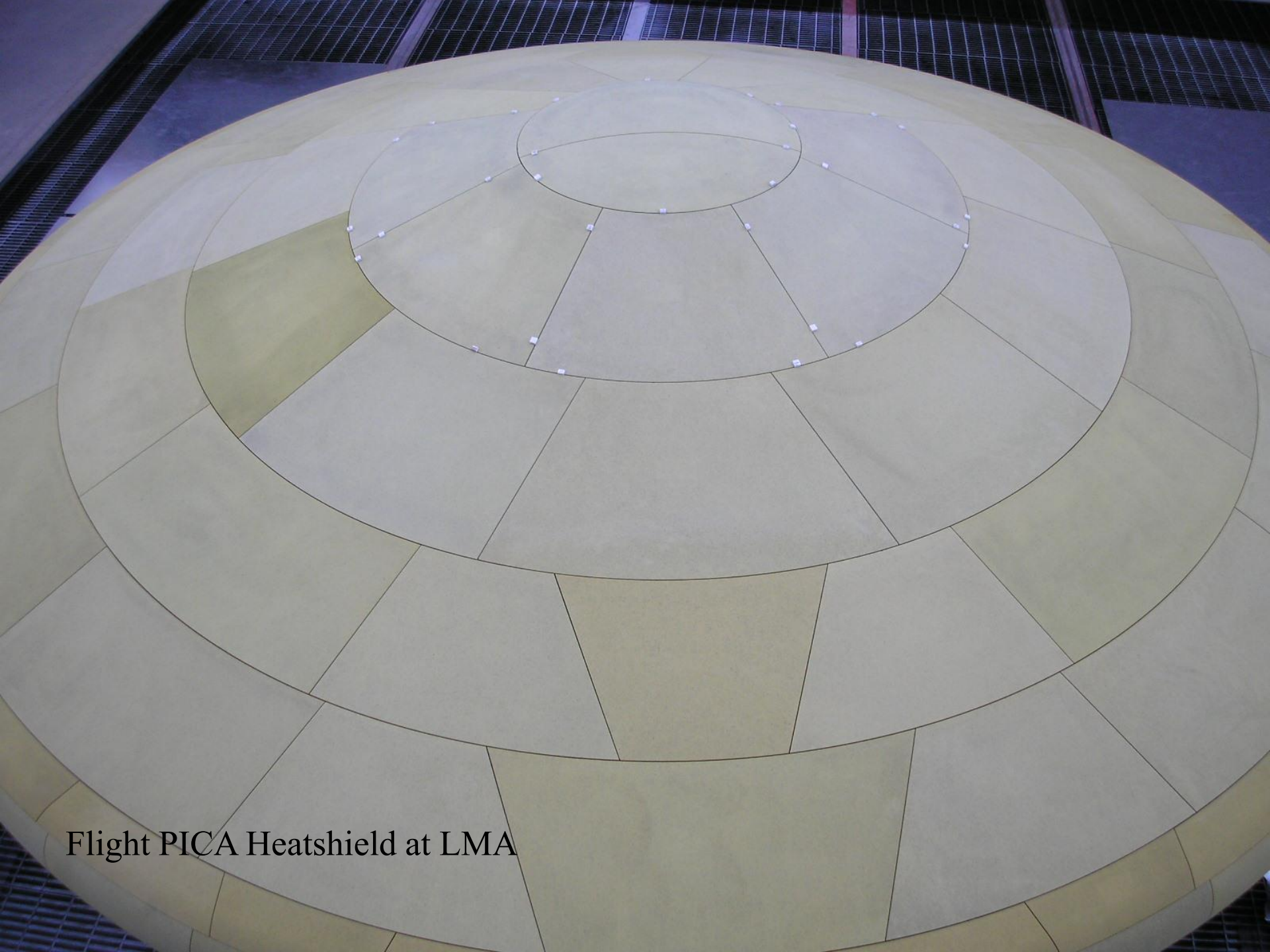
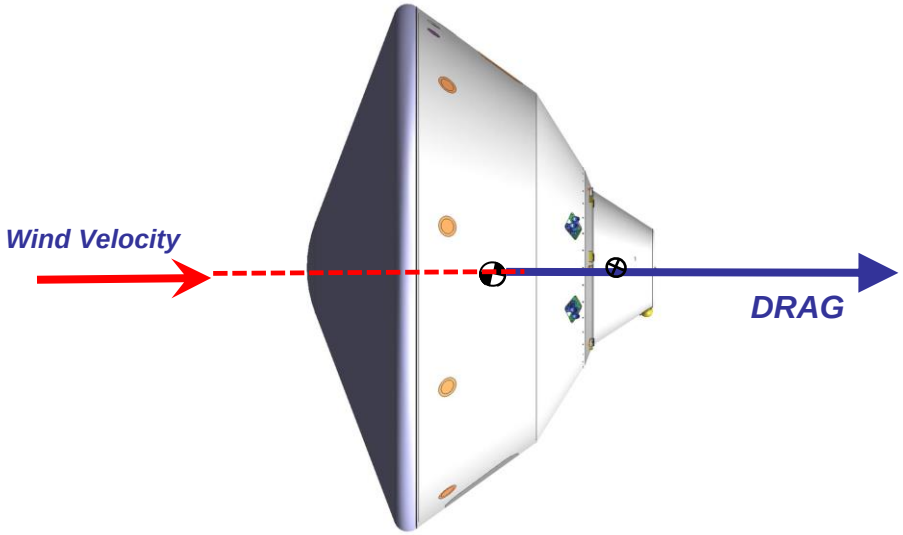
MSL Aeroshell

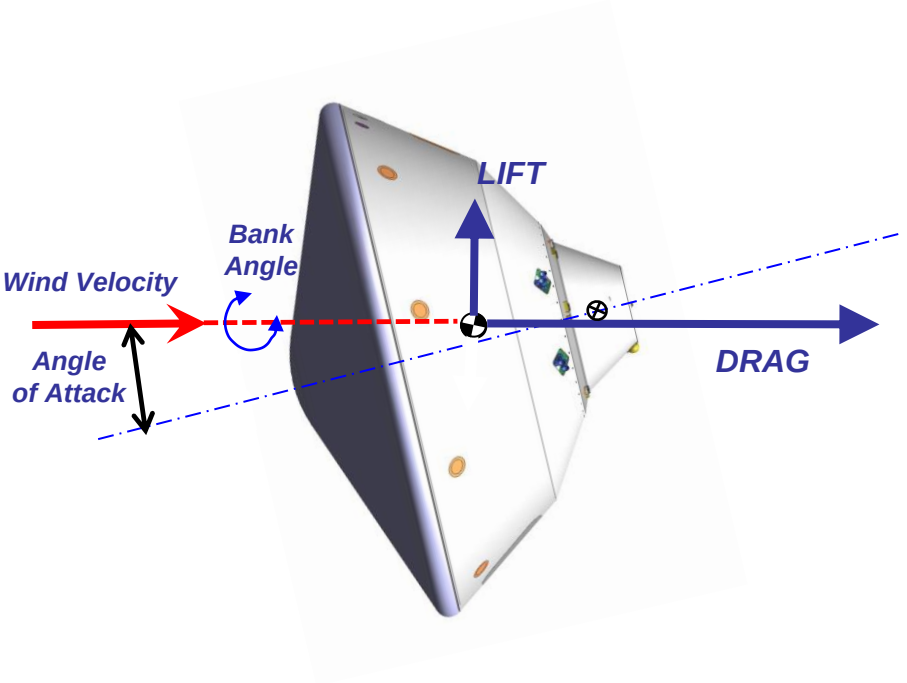


Flight PICA Heatshield at LMA

Ballistic vs. Lifting Entry

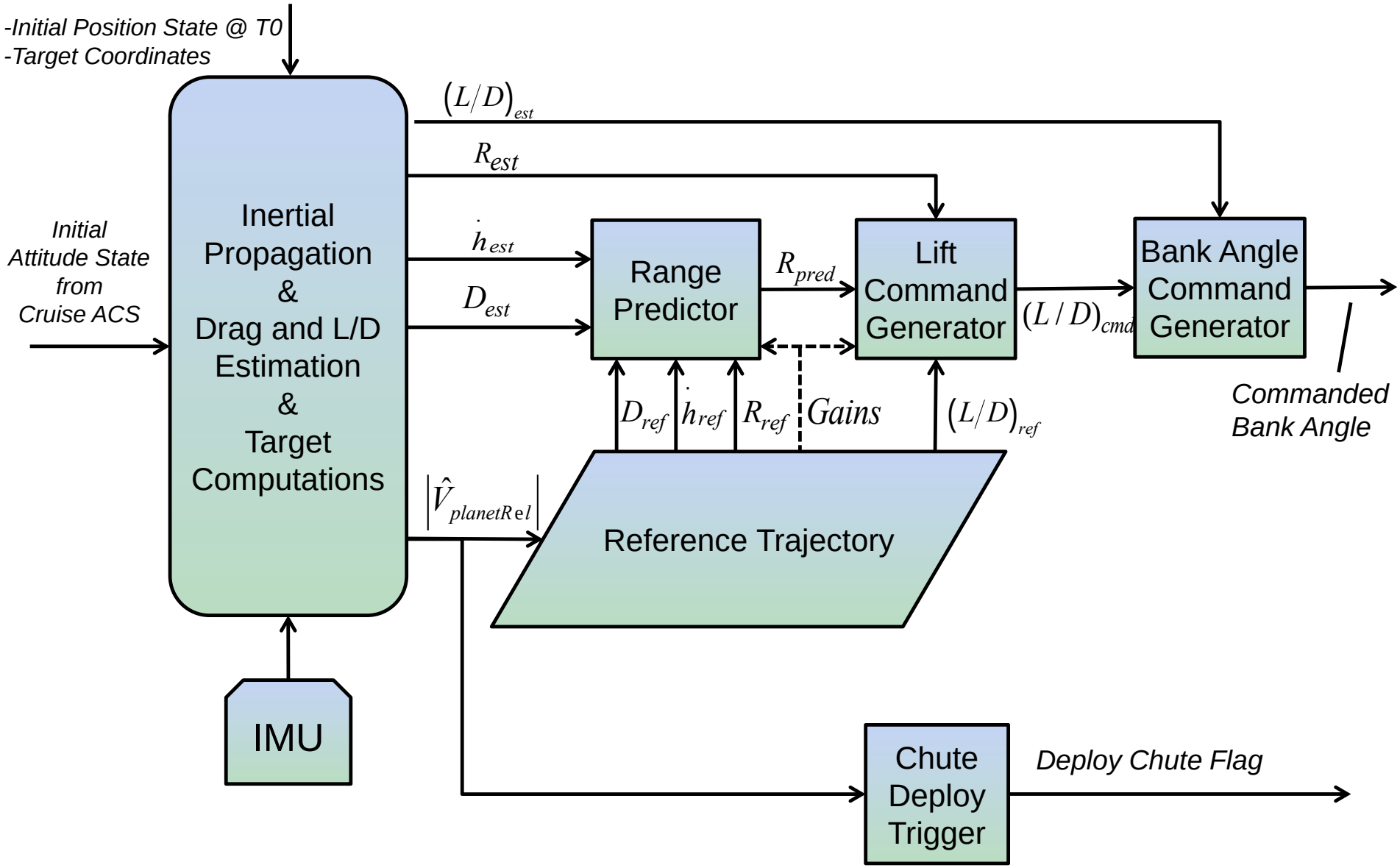


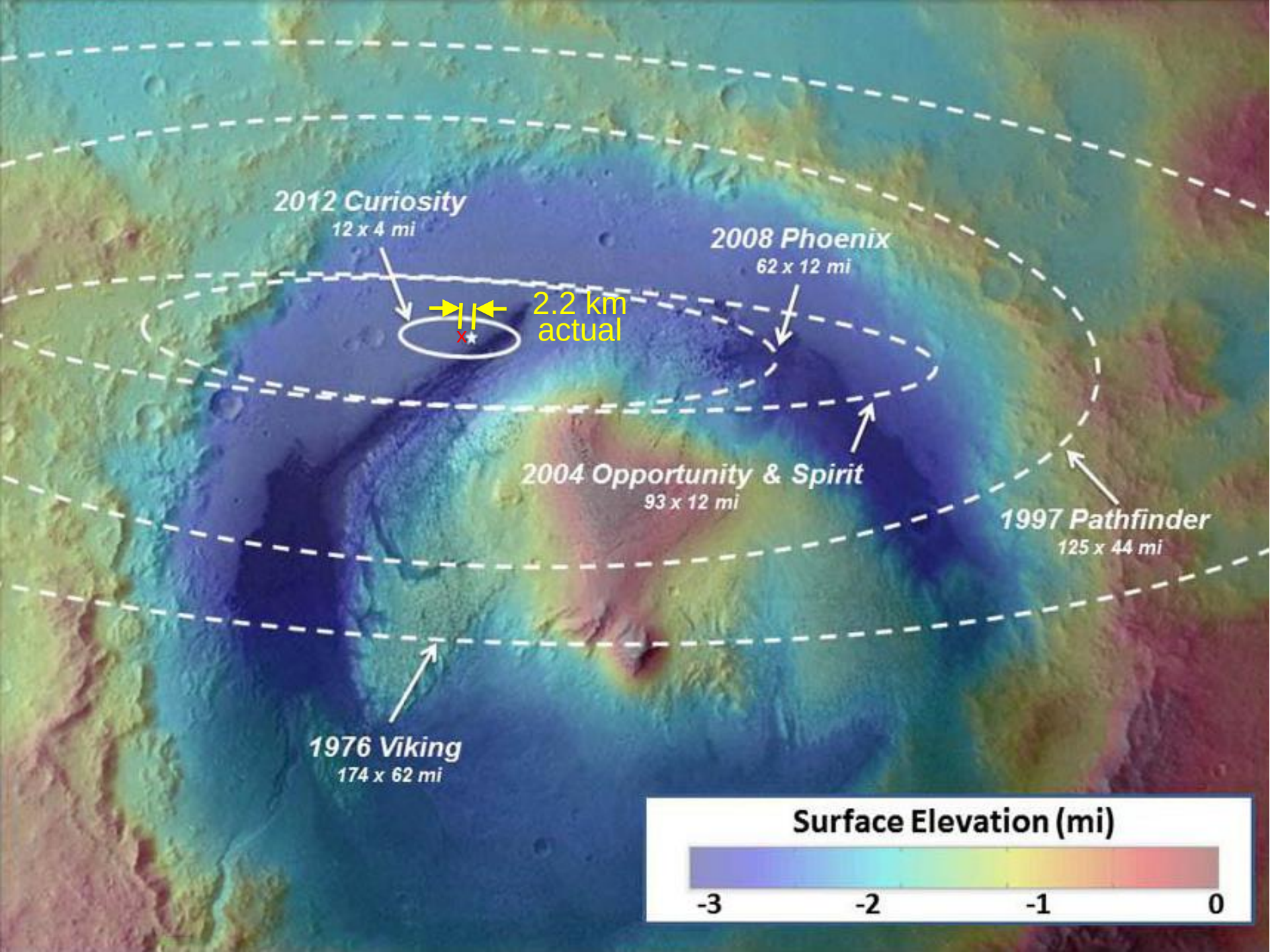
Ballistic Entry
(Pathfinder/MER/Phoenix)



Lifting Entry
(Viking, Curiosity)

Apollo Based Range Entry Guidance

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125 km

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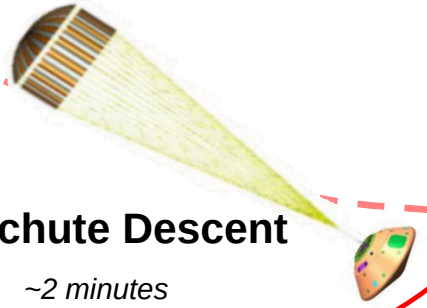

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1.8 km

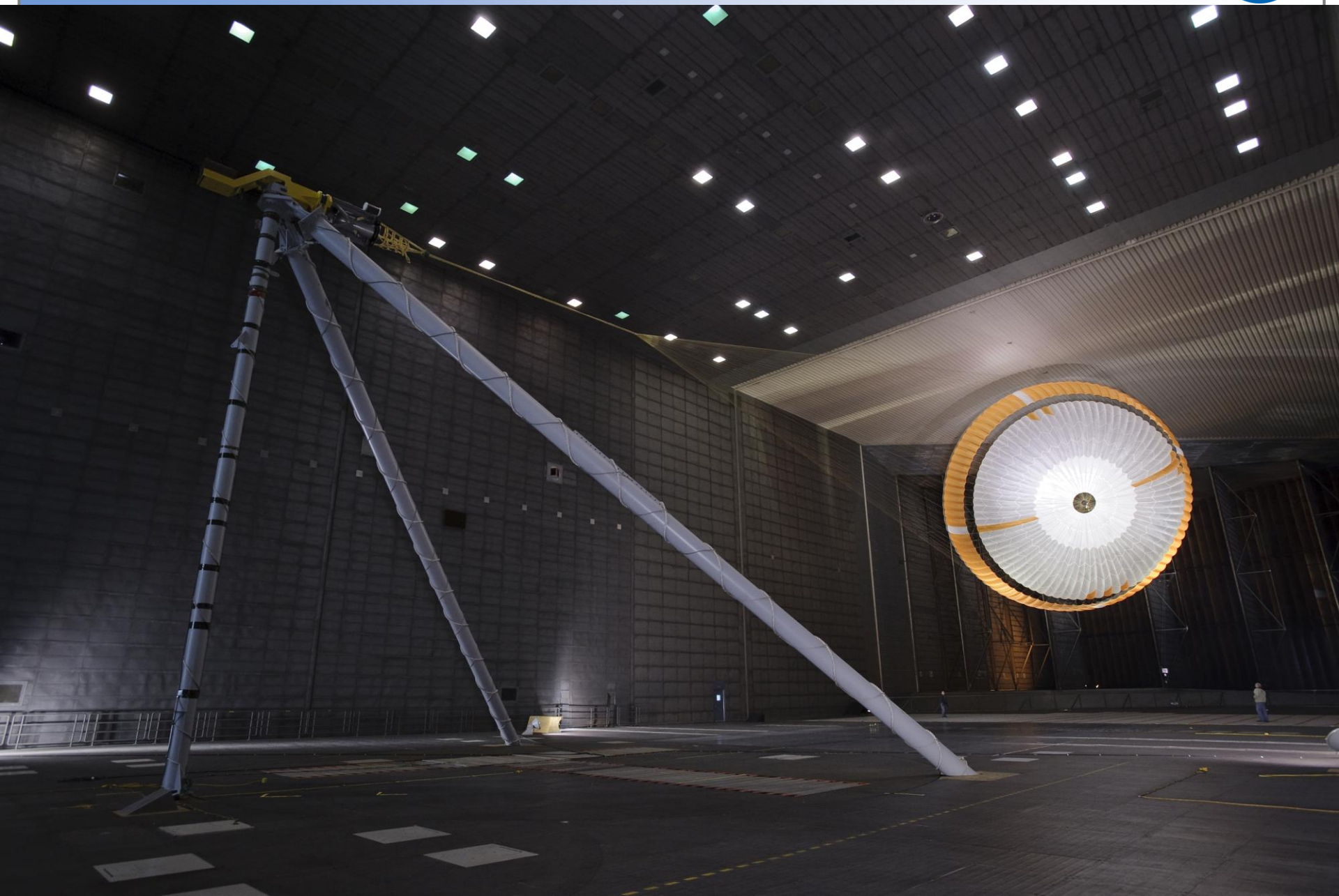
Landing

~1 minute

Touchdown

3 km/h (E = 2 10^{-6}%)

Worlds Largest Supersonic Parachute



Entry, Descent, and Landing Phases

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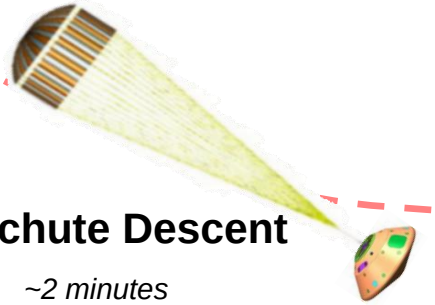

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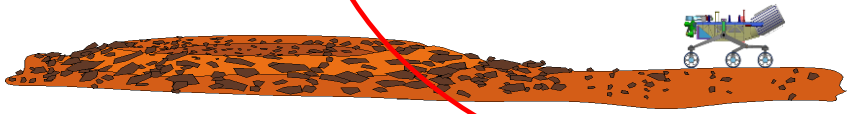
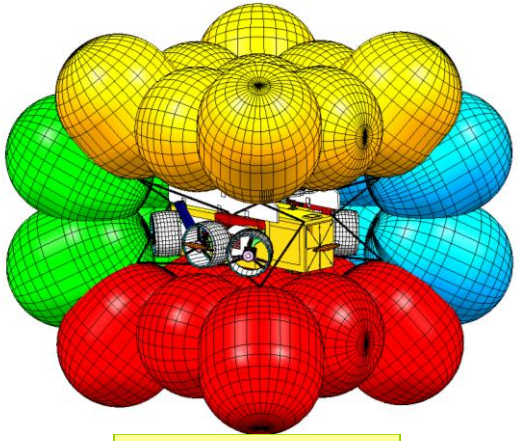
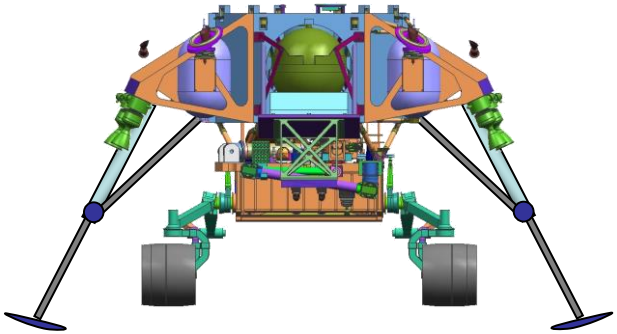


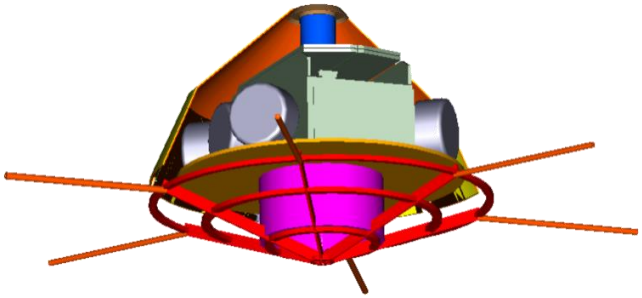
How to land a 1 ton rover?



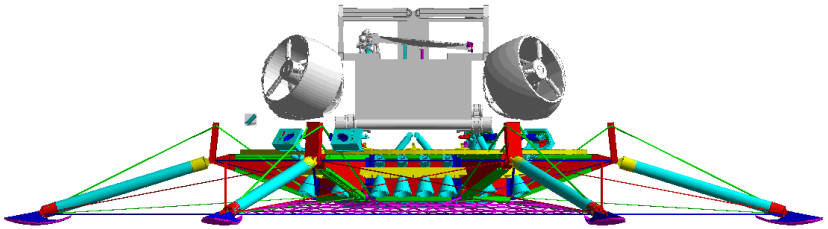
Airbags



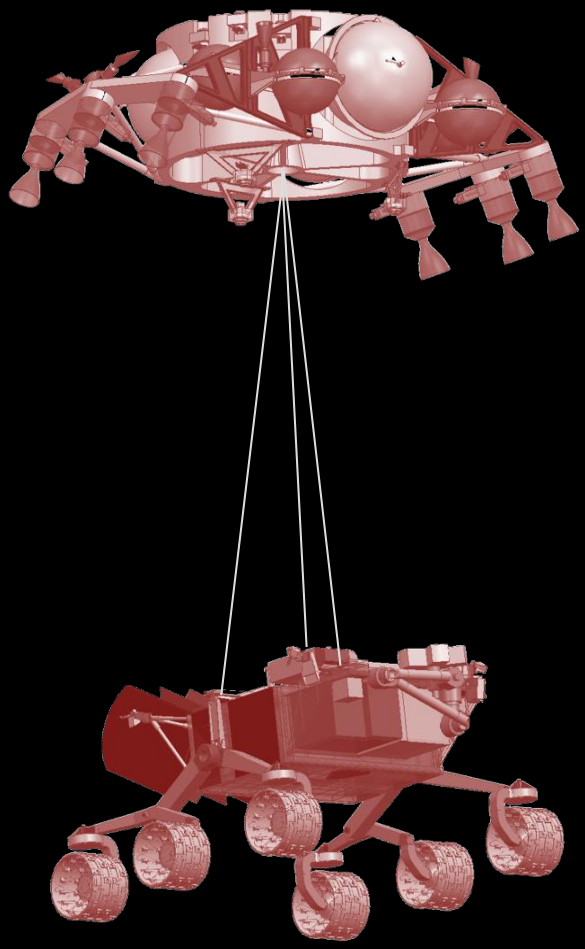
Legs

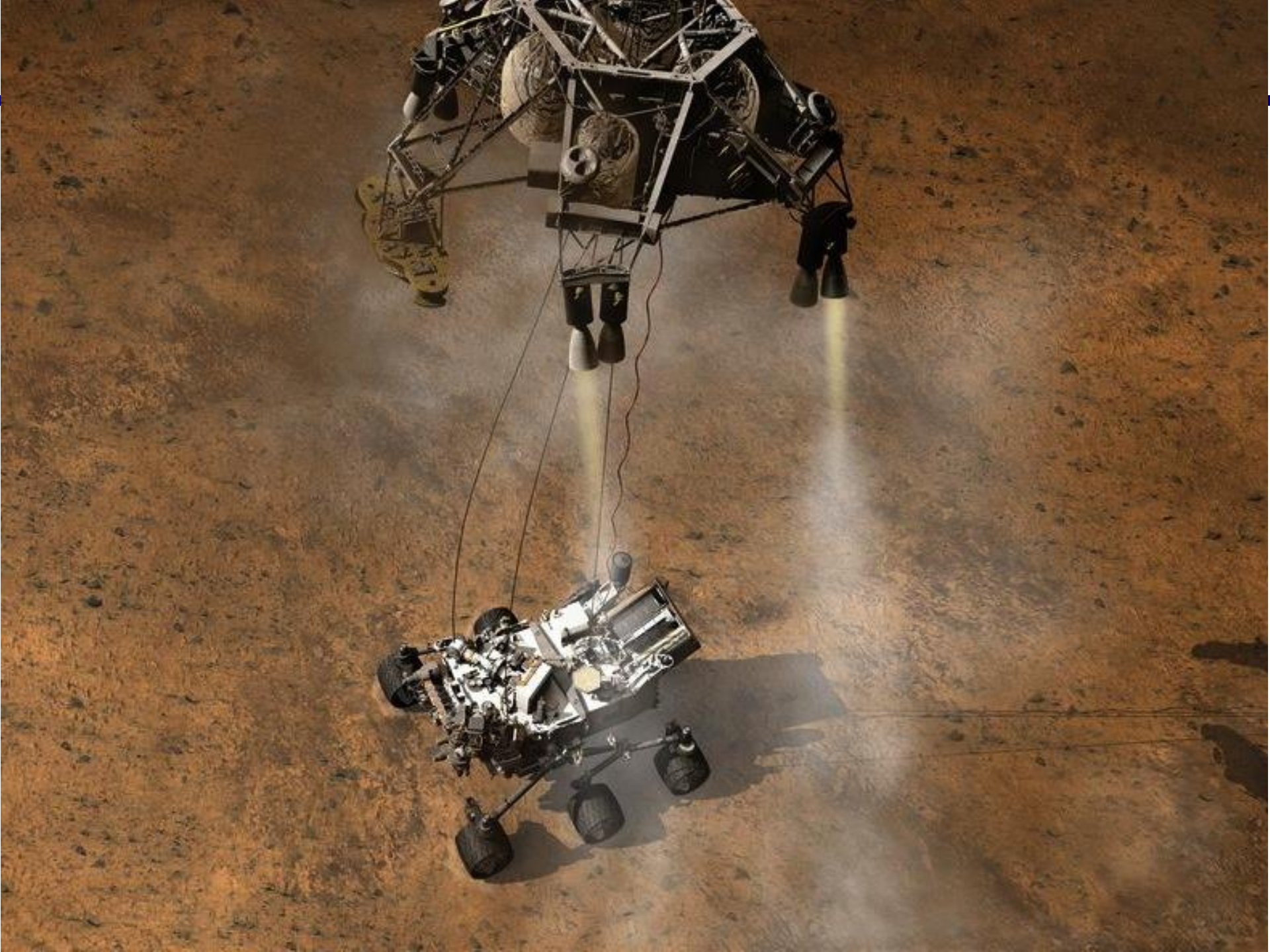


Pallet



2003: The Skycrane maneuver is born



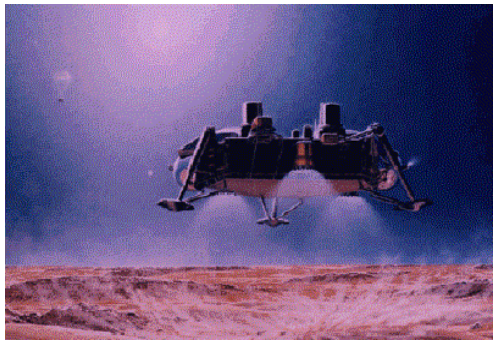


Motivation Behind The SkyCrane

Touchdown Velocity:
- Vv = 12m/sec
- Vh < 16m/sec

- Robust to rocks
- Robust to local slopes
- Proven but hard rover egress
- Sensitive to winds
- Difficult to scale up

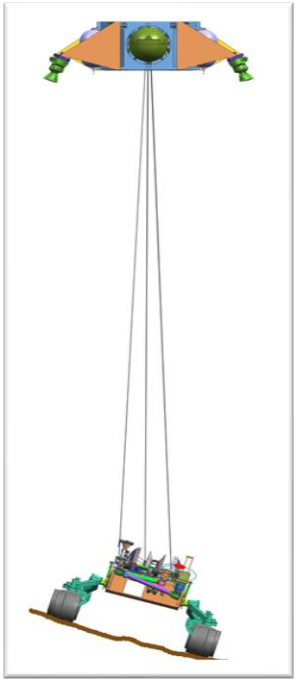
+



Towchdown Velocity:
- Vv = 2.4 m/sec
- Vh < 1.4 m/sec

- Robust to winds
- Dedicated Touchdown Detection
- Sensitive to local slopes
- Sensitive to rocks
- Difficult rover egress

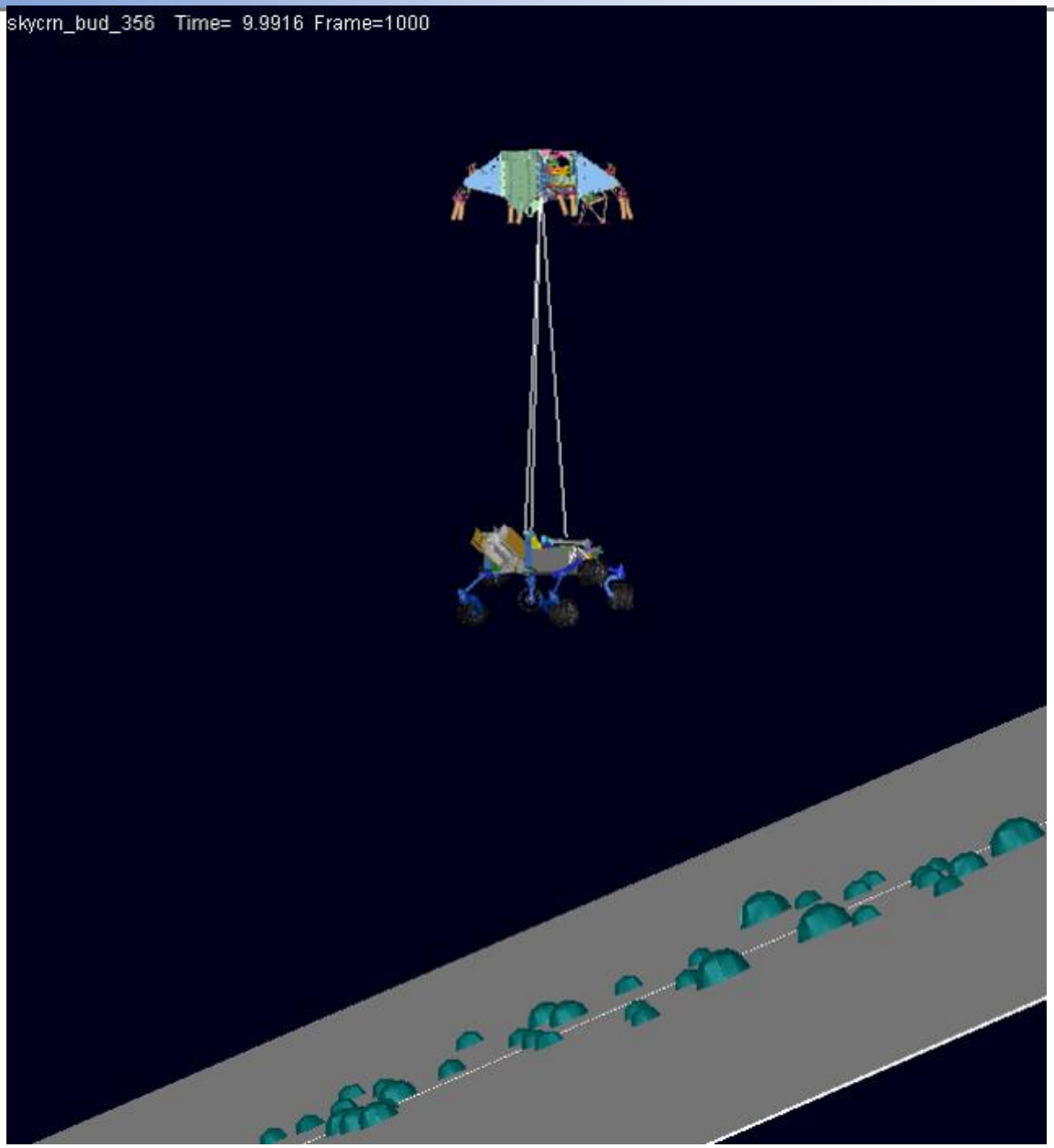
=



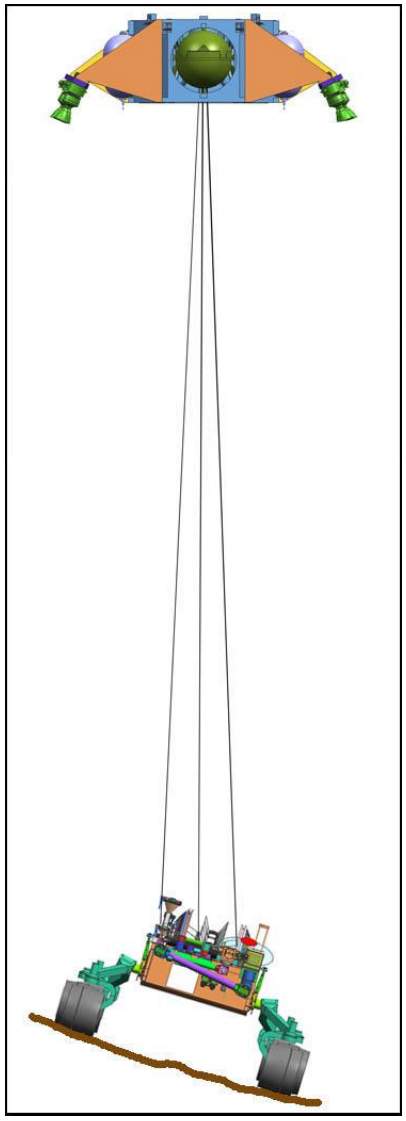
Towchdown Velocity:
- Vv = 0.75 m/sec
- Vh < 0.5 m/sec

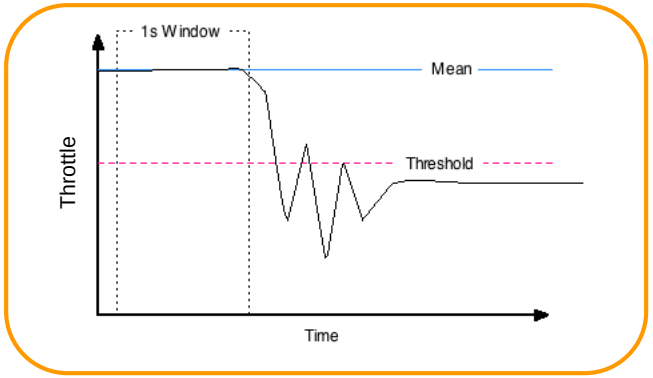
- Robust to winds
- Robust to local slopes
- Robust to rocks
- Simple touchdown detection
- No rover egress problem

Continued Control Through Touchdown

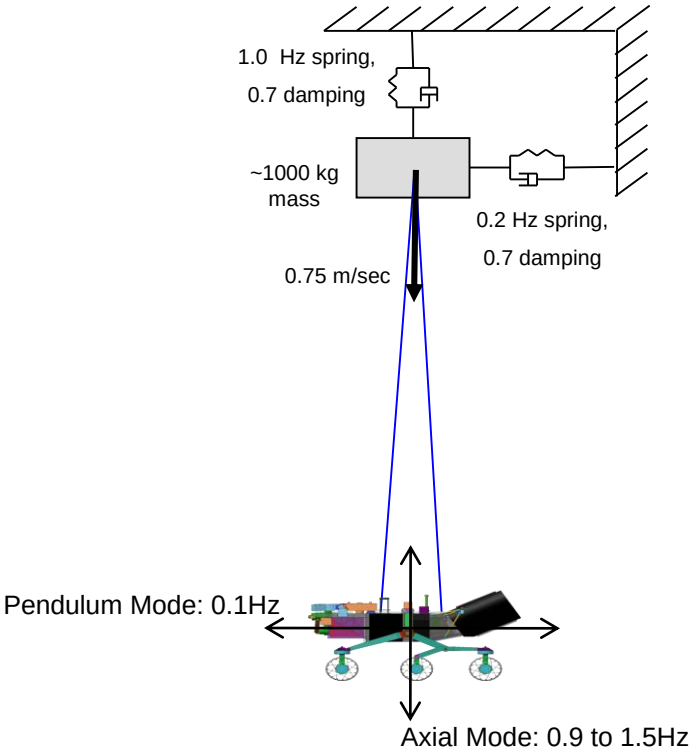


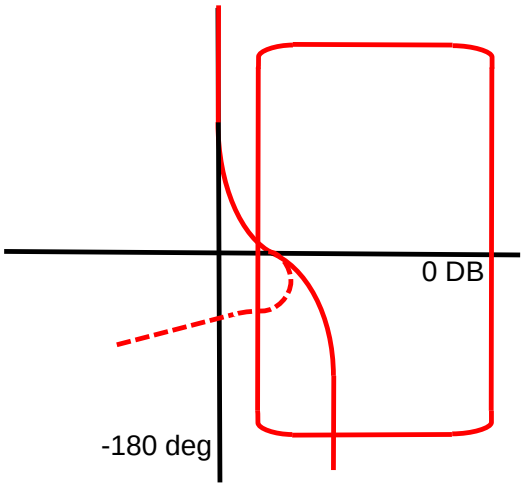
SkyCrane Touchdown Detection





Phase Stabilization of SkyCrane Modes

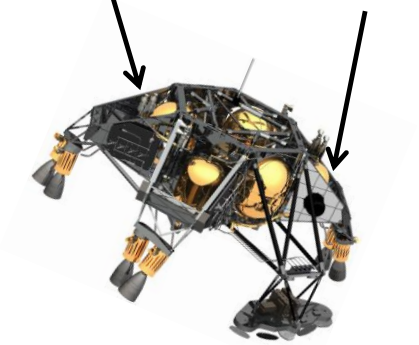


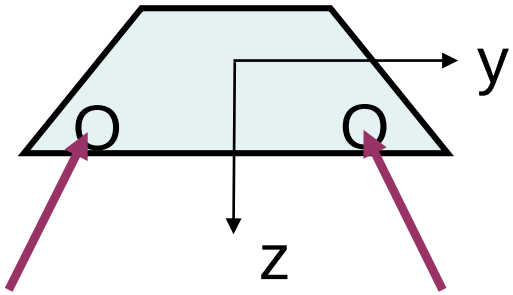


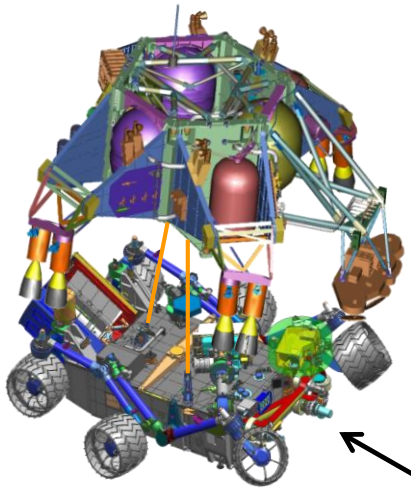
Fly-away

Throttle Valve
Motor Controller

IMU





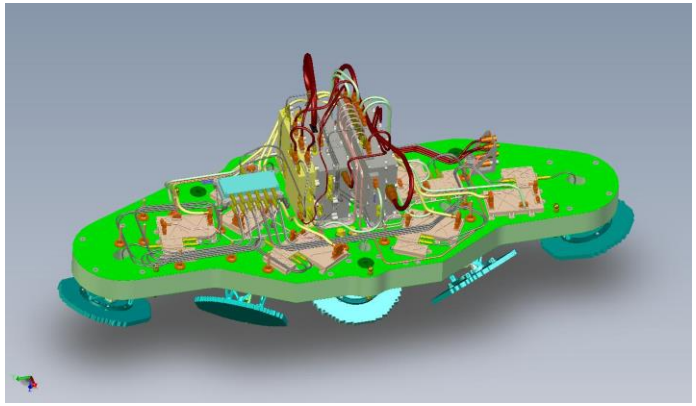


1) **Route IMU through Stage Motor Controller**
2) **Only Attitude Control**
3) **Rotate around body y-axis and hold**
4) **Implicit State Transfer from Rover to DS**
5) **Consume all the fuel**

> 150 m

Rover Computer

Key MSL GN&C/EDL Developments



Terminal Descent Landing Sensor (TDS)

Mars Landing Engine (MLE)

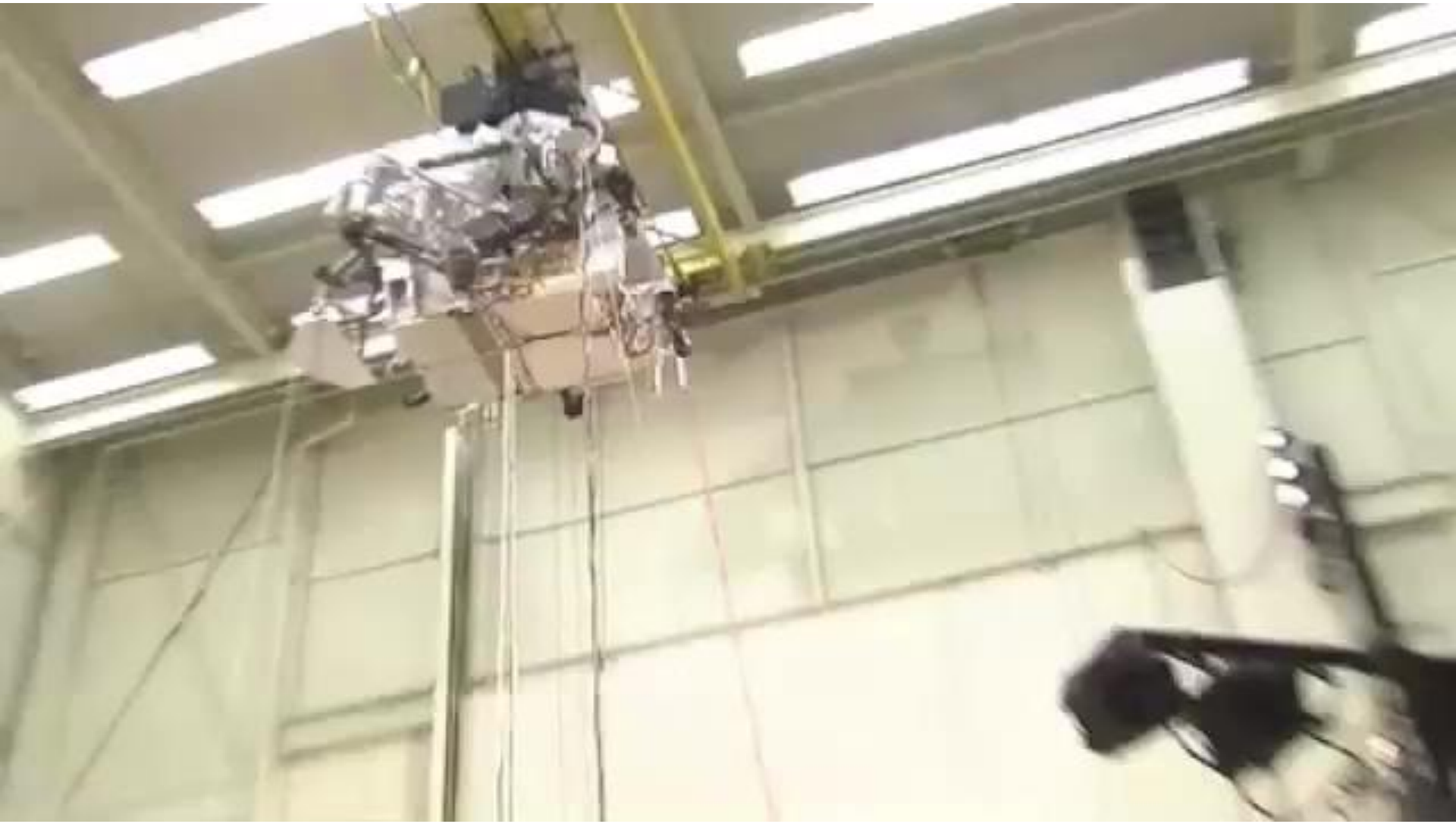
Field Test Venues

China Lake Echo Towers

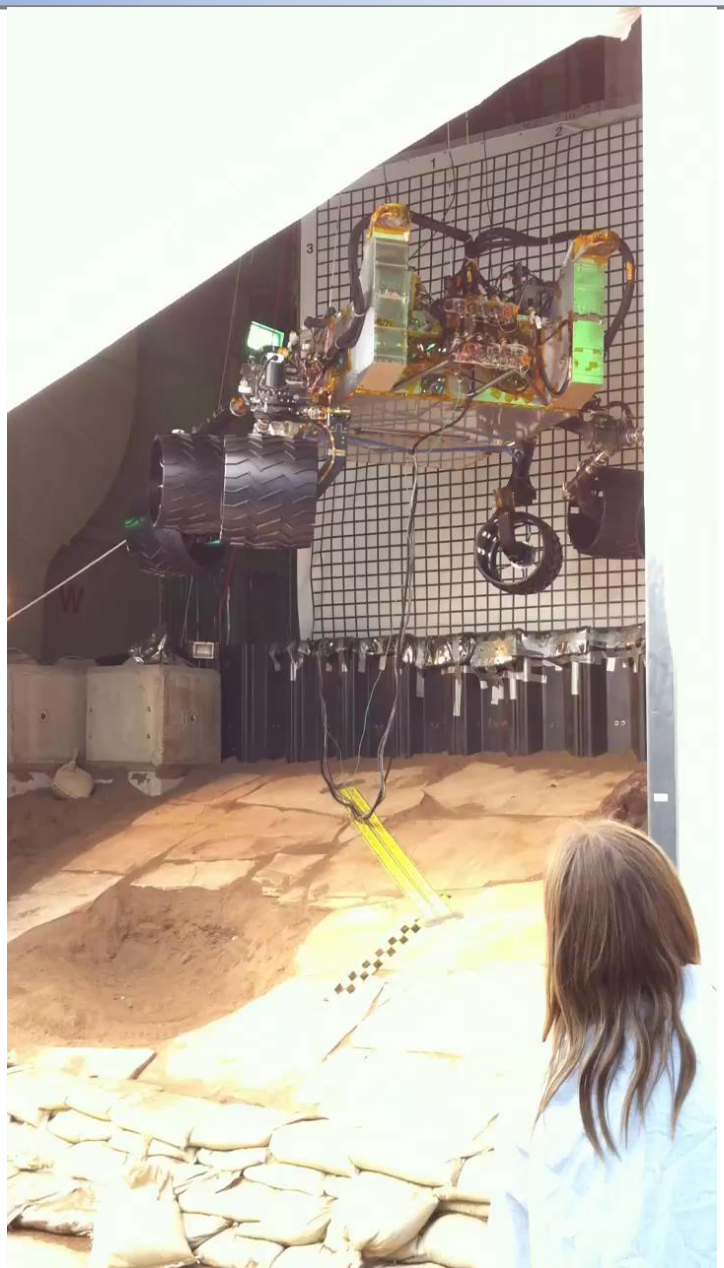
NASA Dryden Flight Research Center F/A-18

Eurocopter AS350 AStar Helicopter

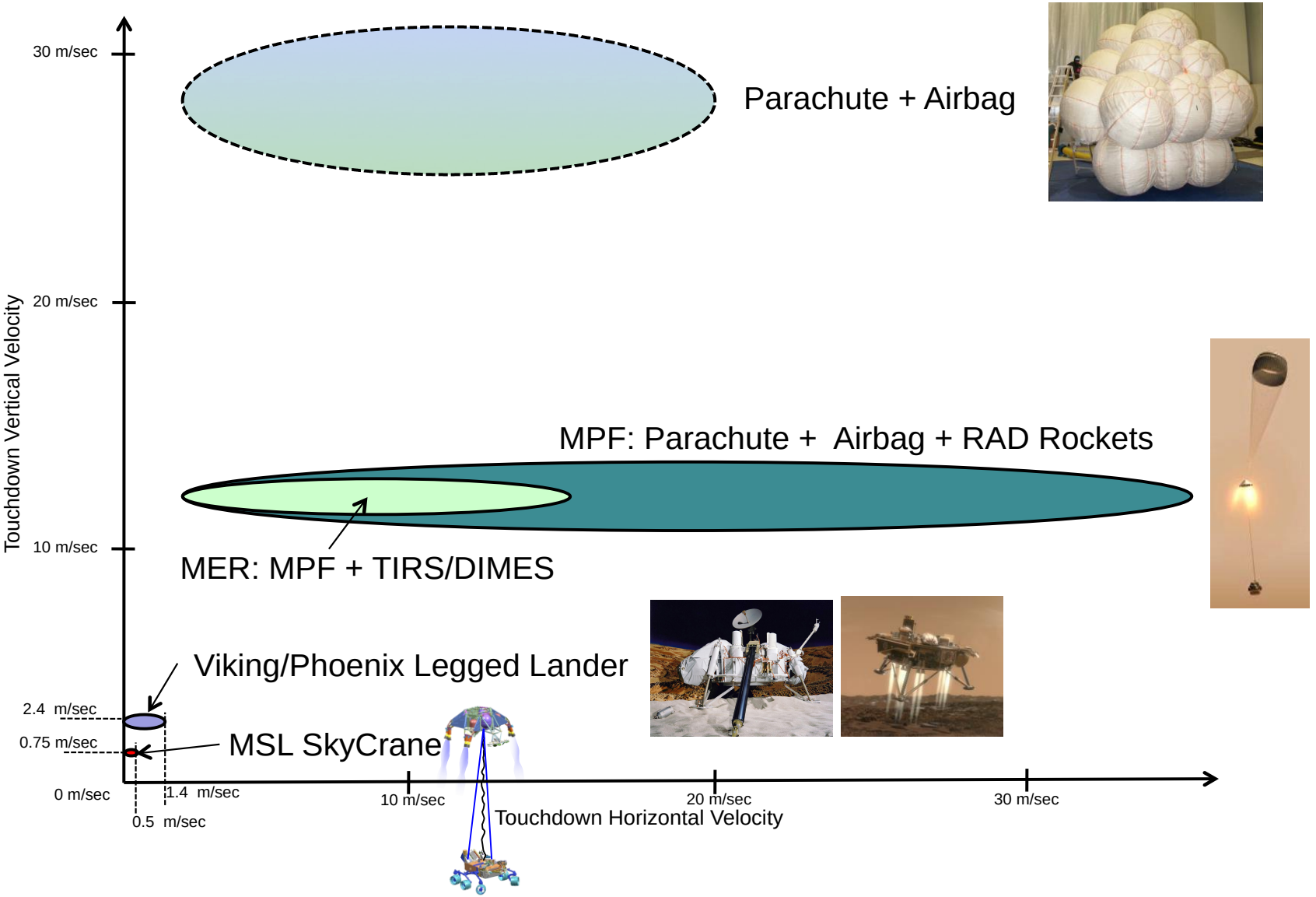
Full Motion Test

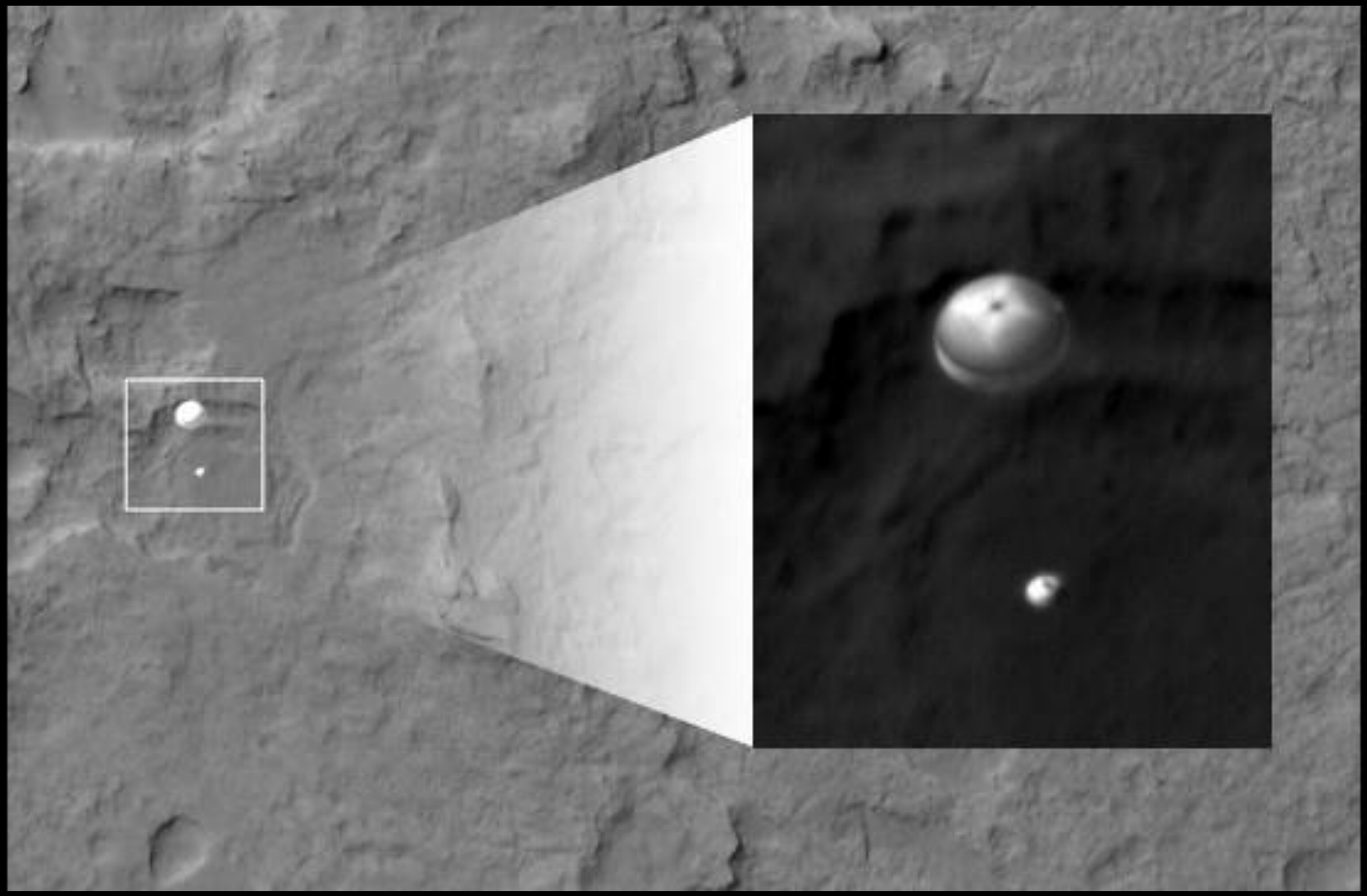


Touchdown Test



History of Mars Touchdown Velocities



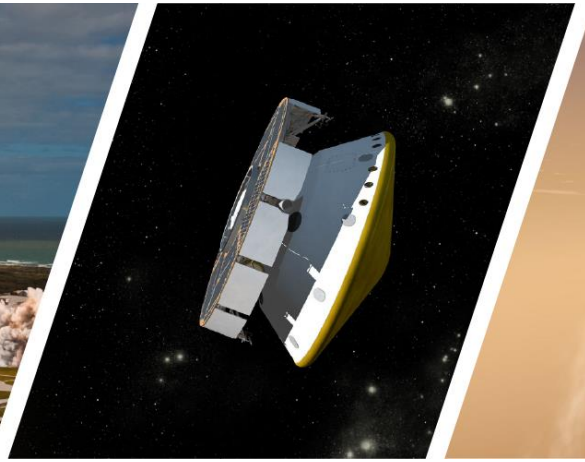


JPL
Jet Propulsion Laboratory
California Institute of Technology

Mount Sharp

NASA

Mars 2020 Mission Overview

LAUNCH

- MSL Class/Capability LV
- Period: Jul/Aug 2020

CRUISE/APPROACH

- 7.5 month cruise
- Arrive Feb 2021

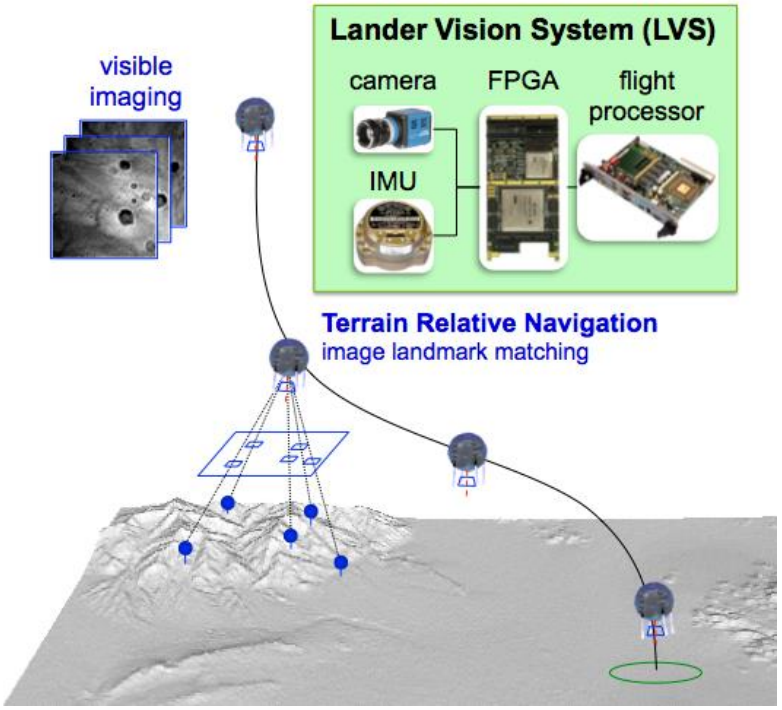
ENTRY, DESCENT & LANDING

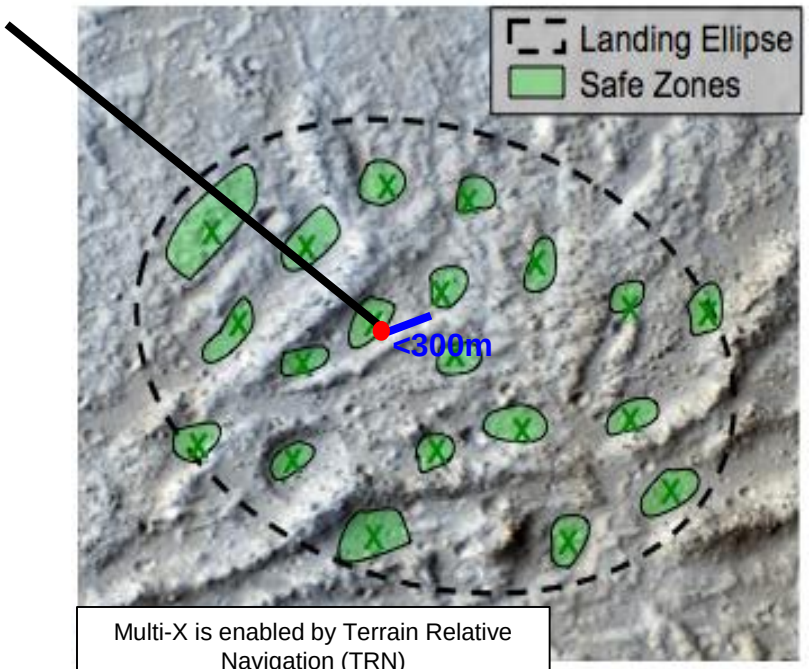
- MSL EDL system (Range Trigger baselined, Terrain Relative Navigation funded thru PDR): guided entry and powered descent/Sky Crane
- 16 x 14 km landing ellipse (range trigger baselined)
- Access to landing sites $\pm 30^{\circ}$ latitude, $\leq$ -0.5 km elevation
- Curiosity-class Rover

SURFACE MISSION

- 20 km traverse distance capability
- Seeking signs of past life
- Returnable cache of samples
- Prepare for human exploration of Mars

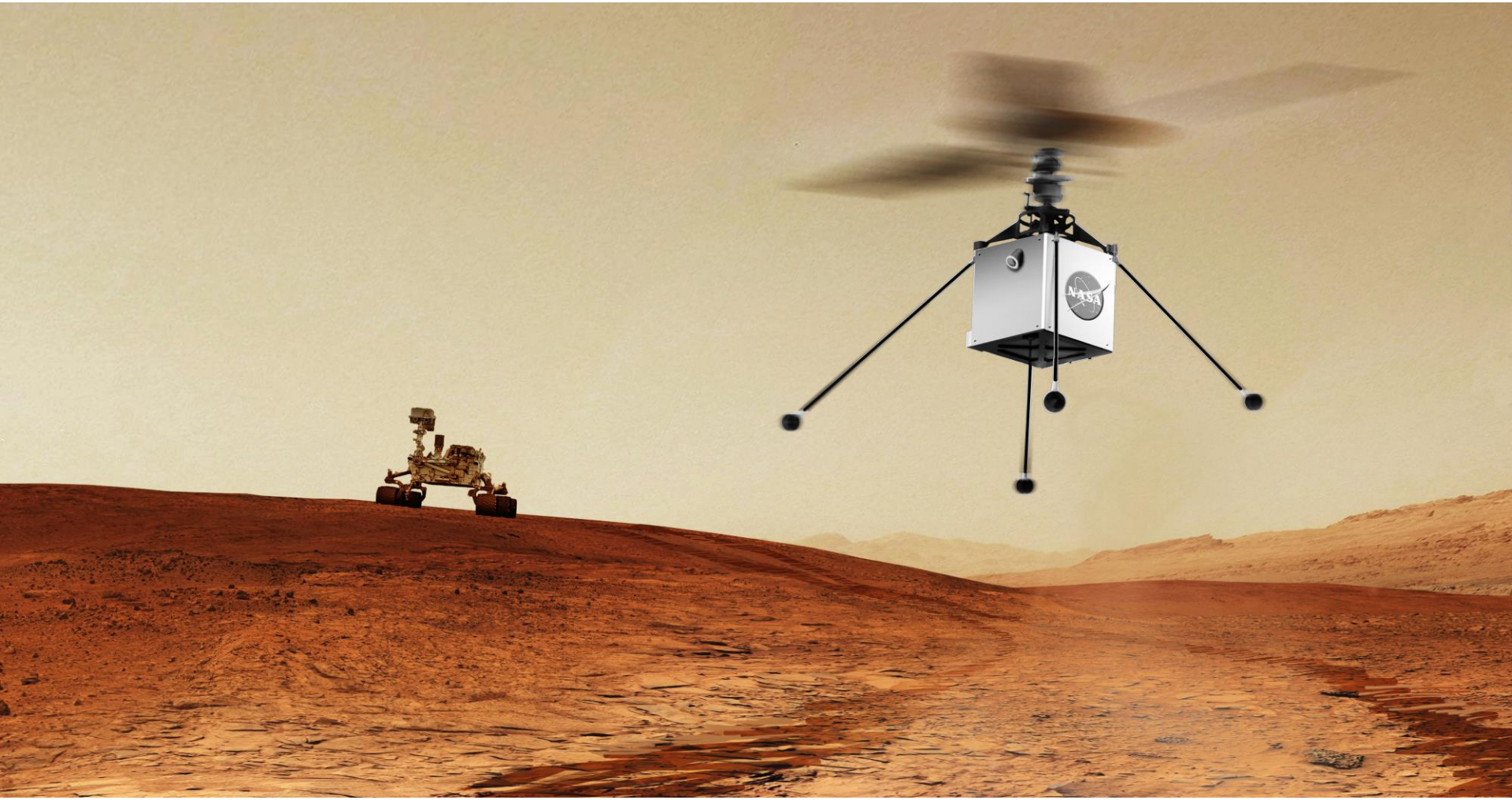
Terrain Relative Navigation



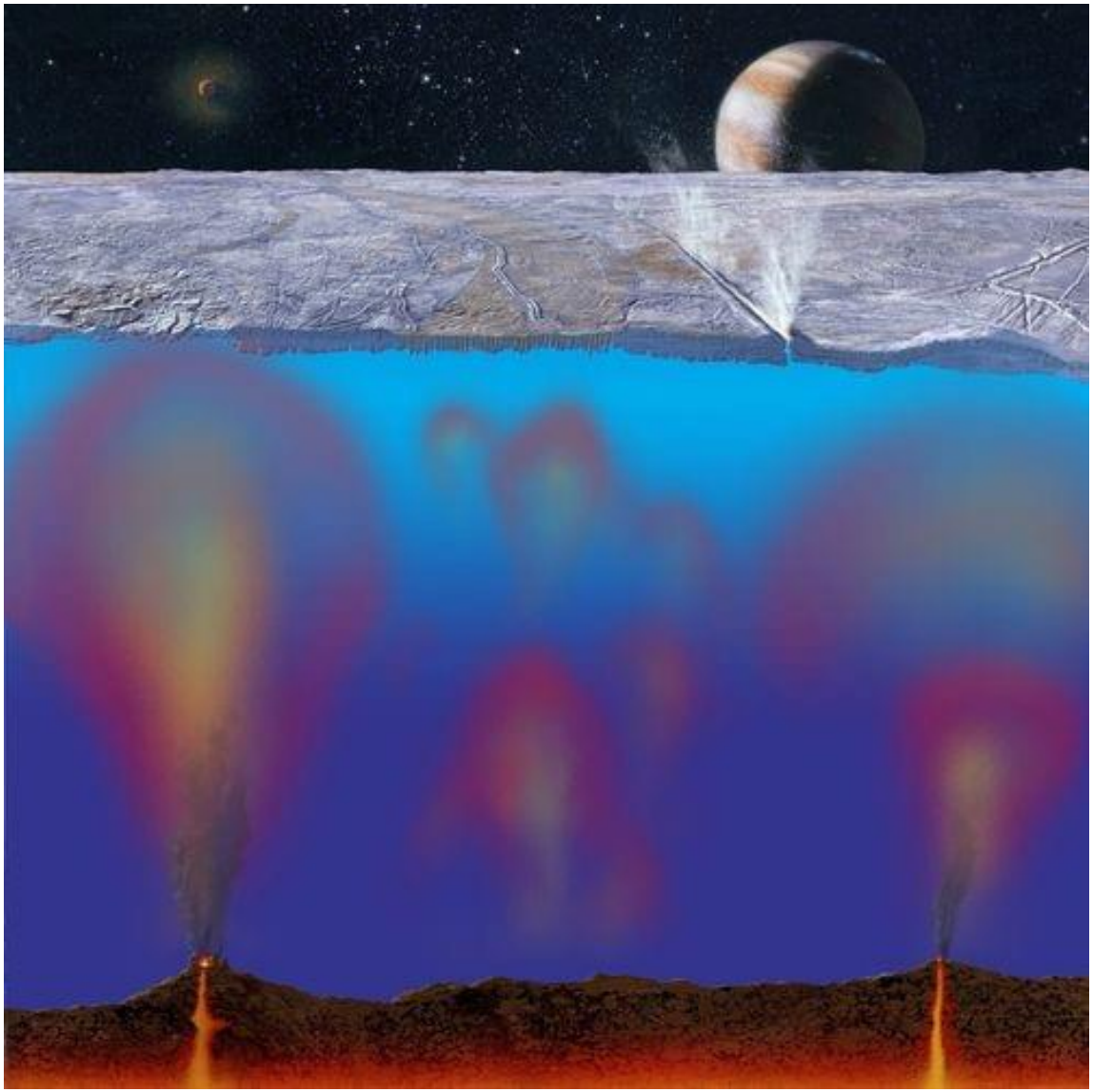


Multi-X is enabled by Terrain Relative Navigation (TRN)

Mars Helicopter for 2020!



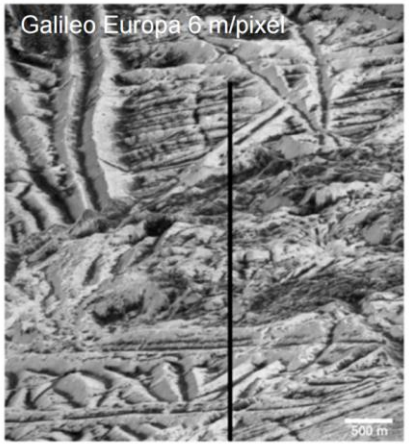
Why Explore Europa?



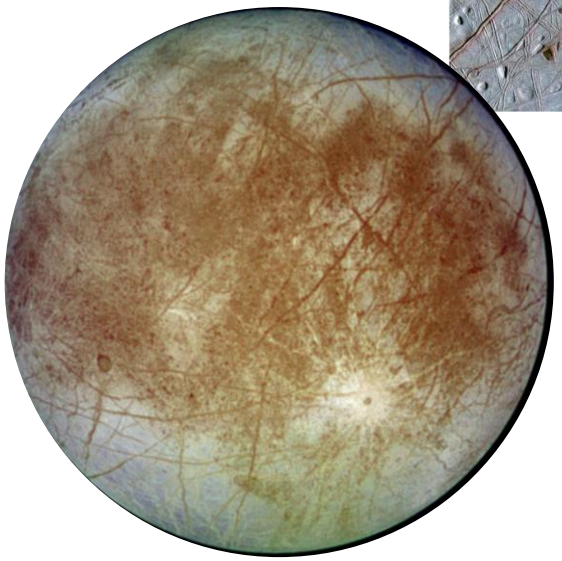
De-Orbit, Descent, and Landing (DDL) Challenges

Jet Propulsion Laboratory
California Institute of Technology

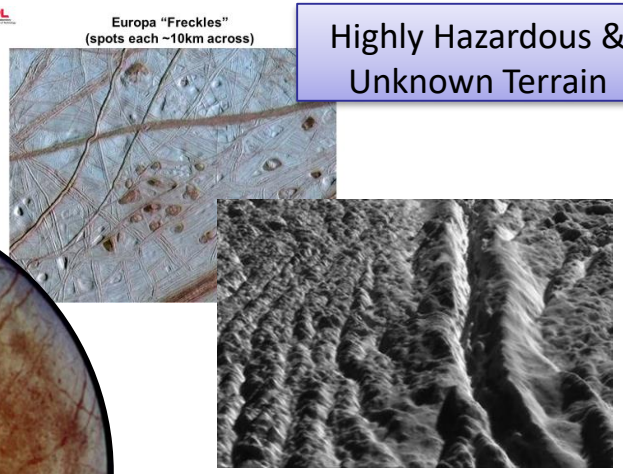
Current Lack of High-res Recon Maps



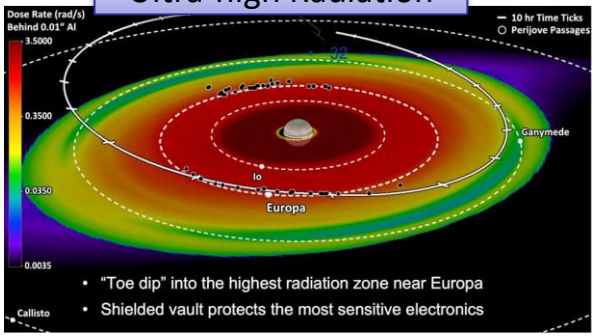
Highest Resolution Europa image currently available



Highly Hazardous & Unknown Terrain



Ultra-high Radiation

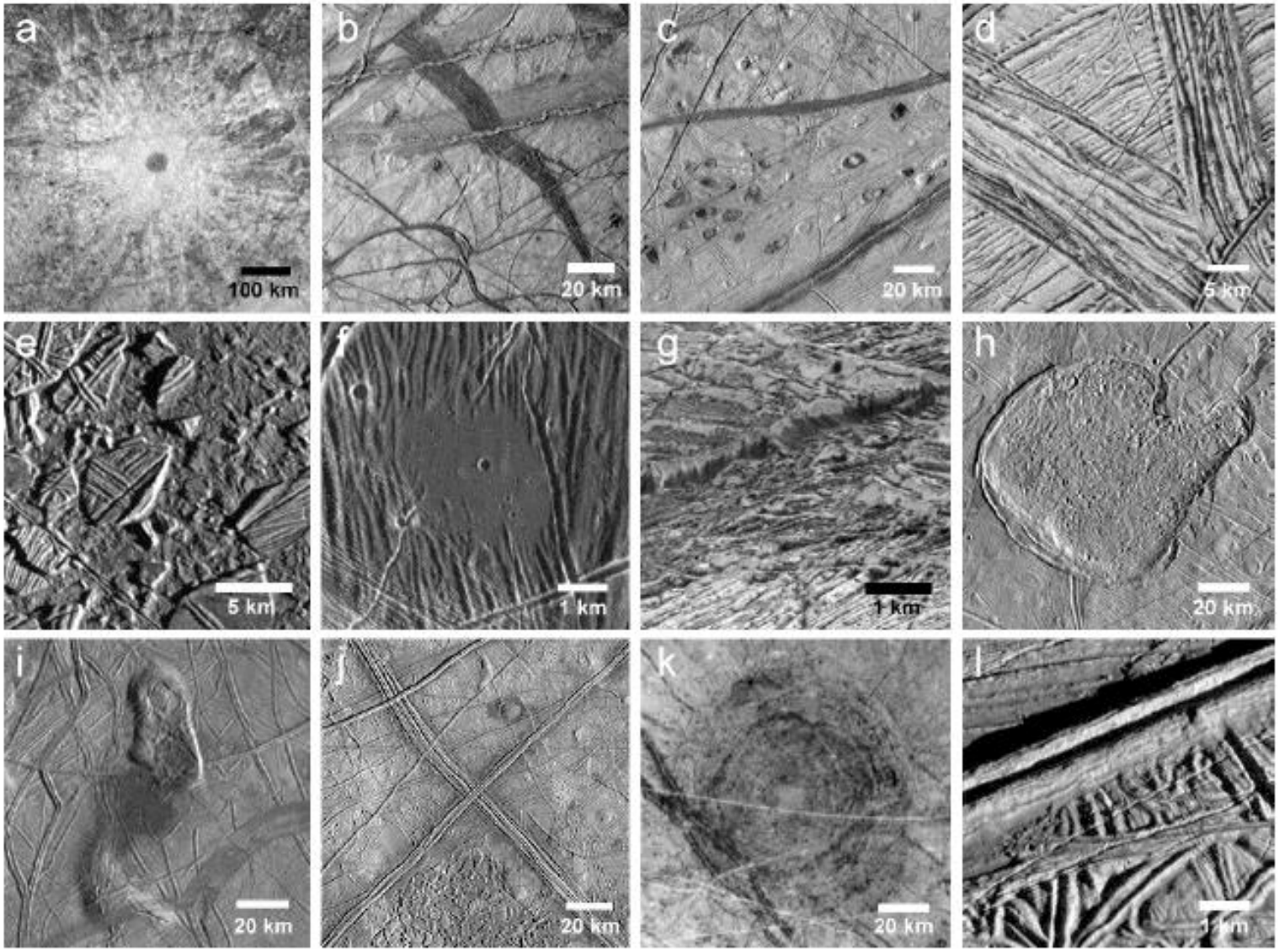


Large Propulsive Delta-V

Artist's Concept

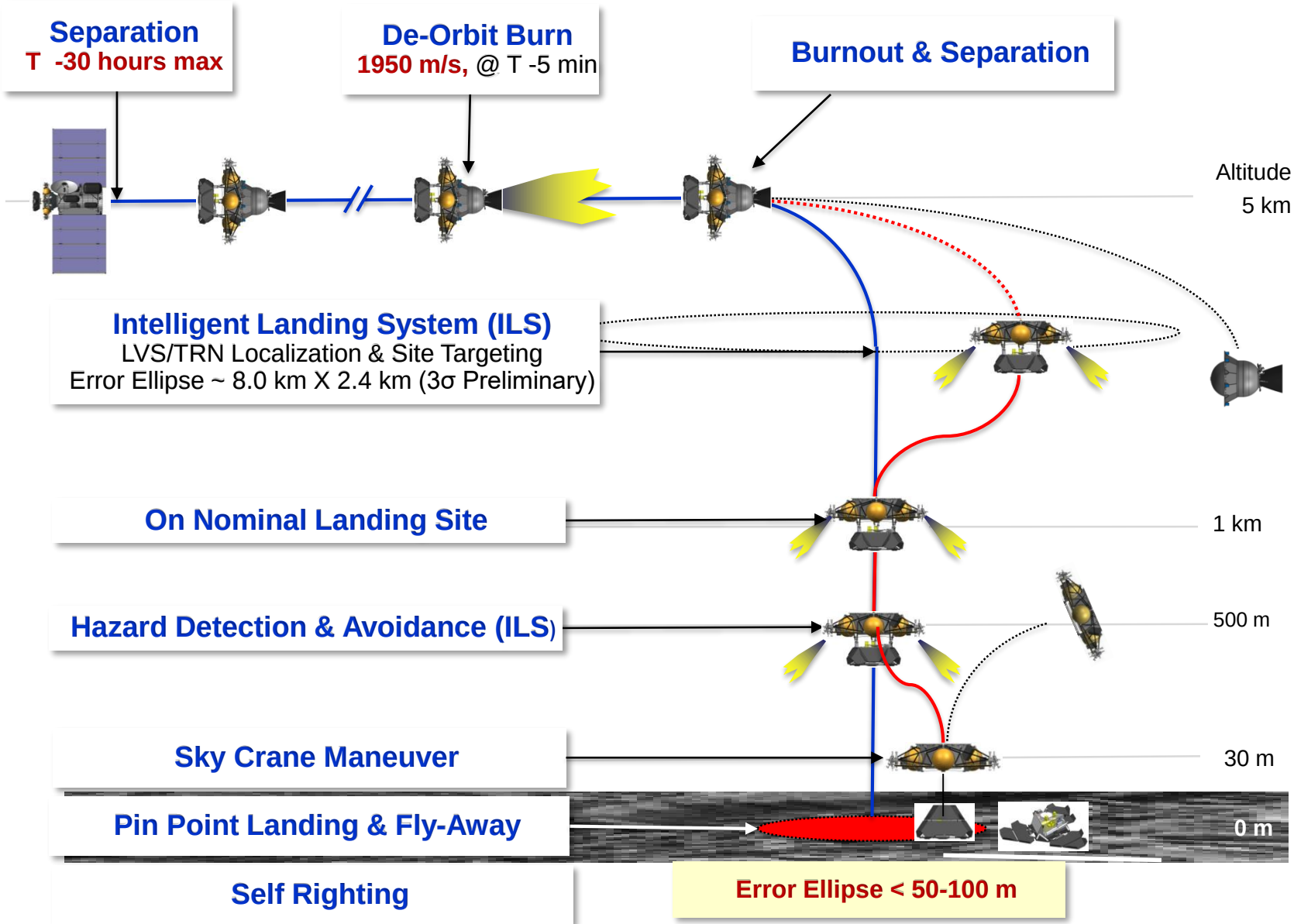
Limited Lander SWAP Resources

Examples of Europa Terrain



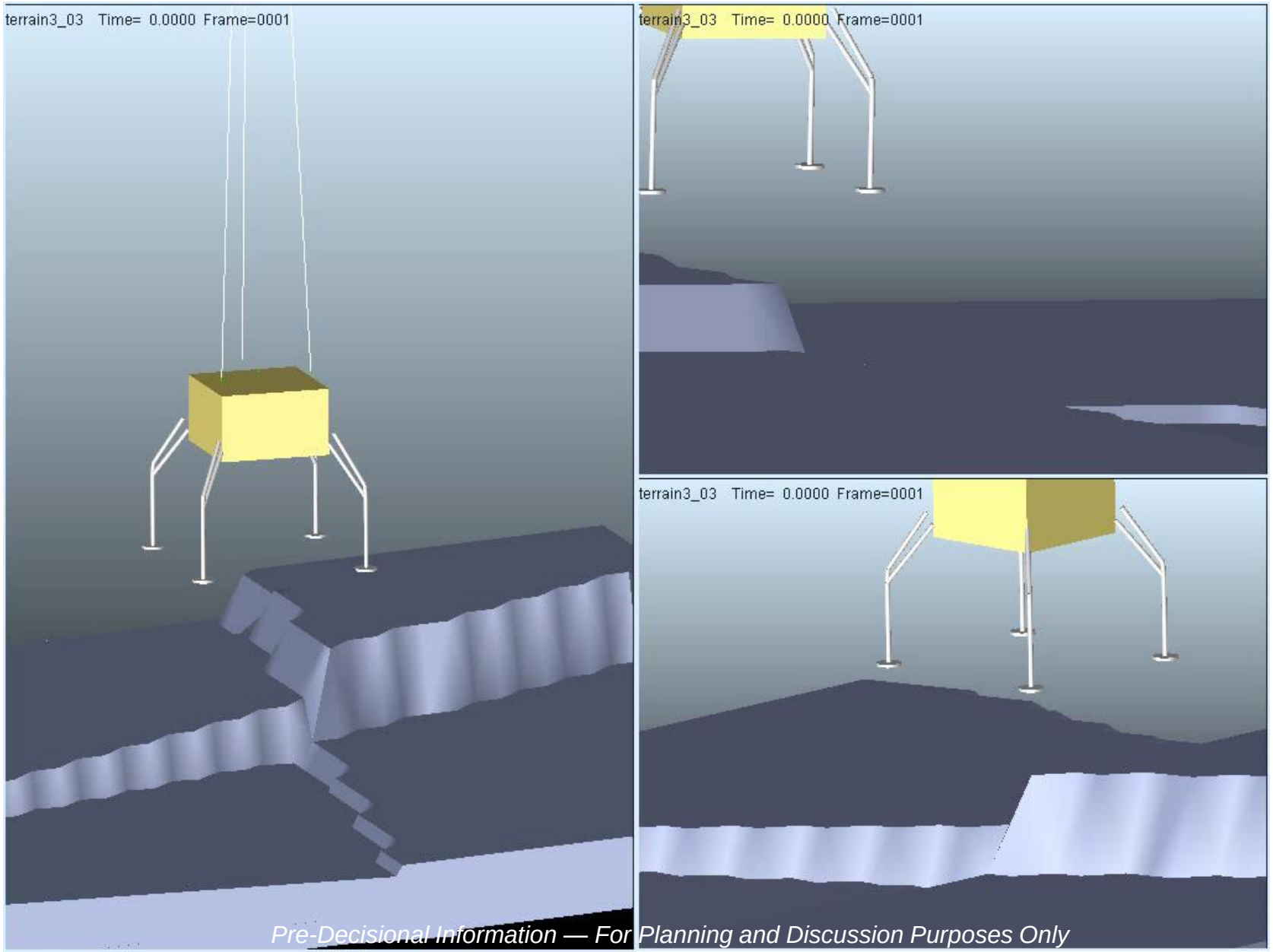
Penitentes

Precision Landing with TRN and HDA

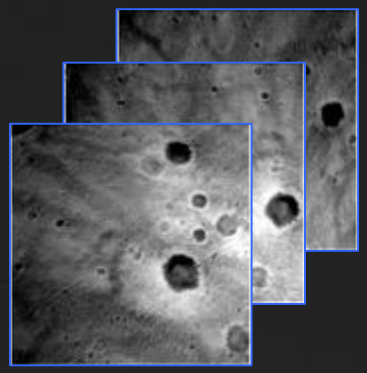


Skycrane with CRICKET

SkyCrane with Landing Stabilizers



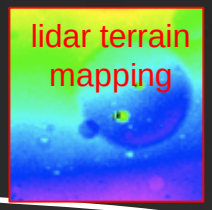
Intelligent Landing System (ILS) Concept of Operations



visible descent imaging

Terrain Relative Navigation (TRN)
image landmark matching

Velocimetry
image feature tracking

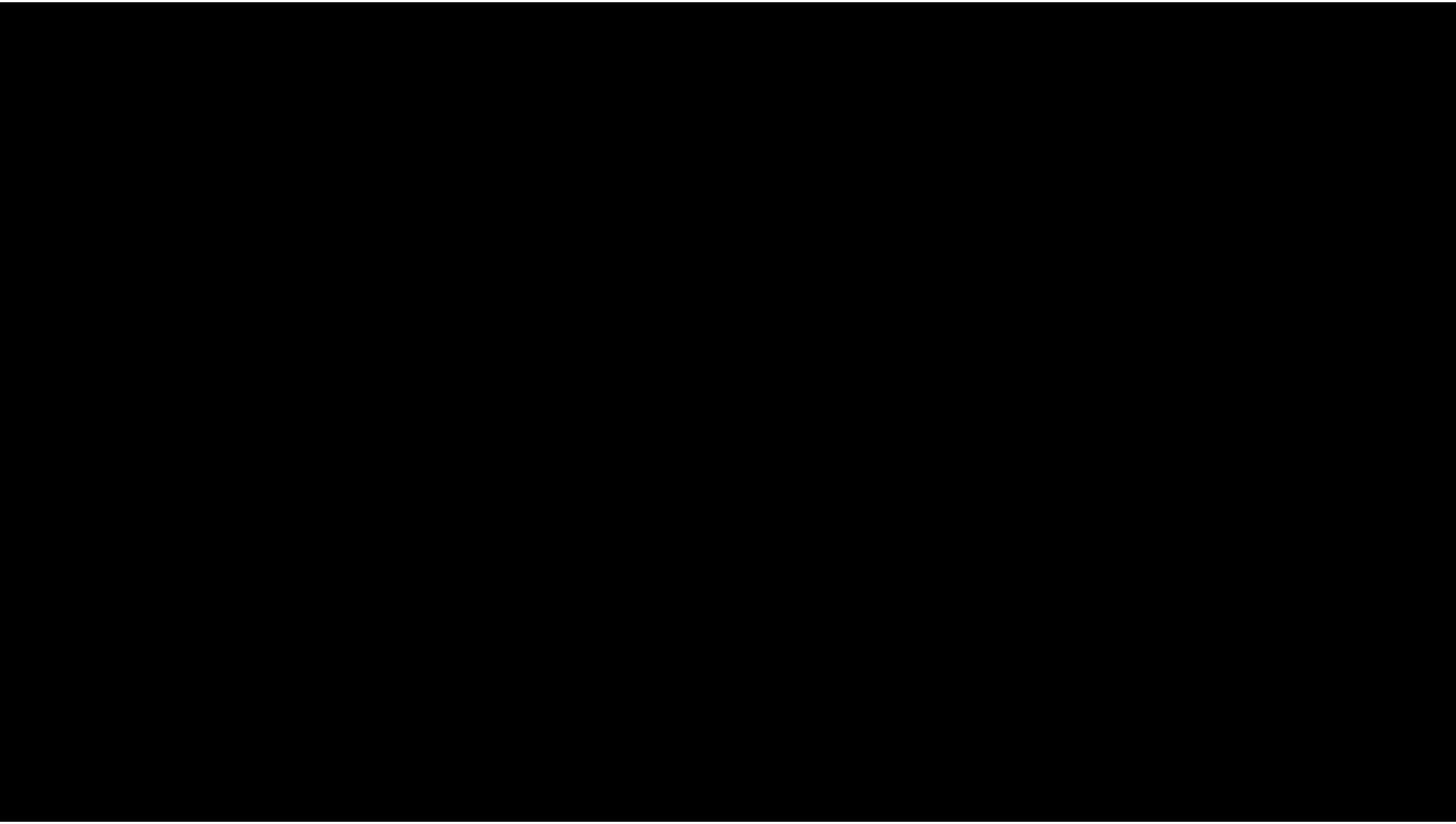


Hazard Detection (HD)
wide beam lidar

Altimetry
narrow beam lidar

Dual Function Lidar

Curiosity Landing



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