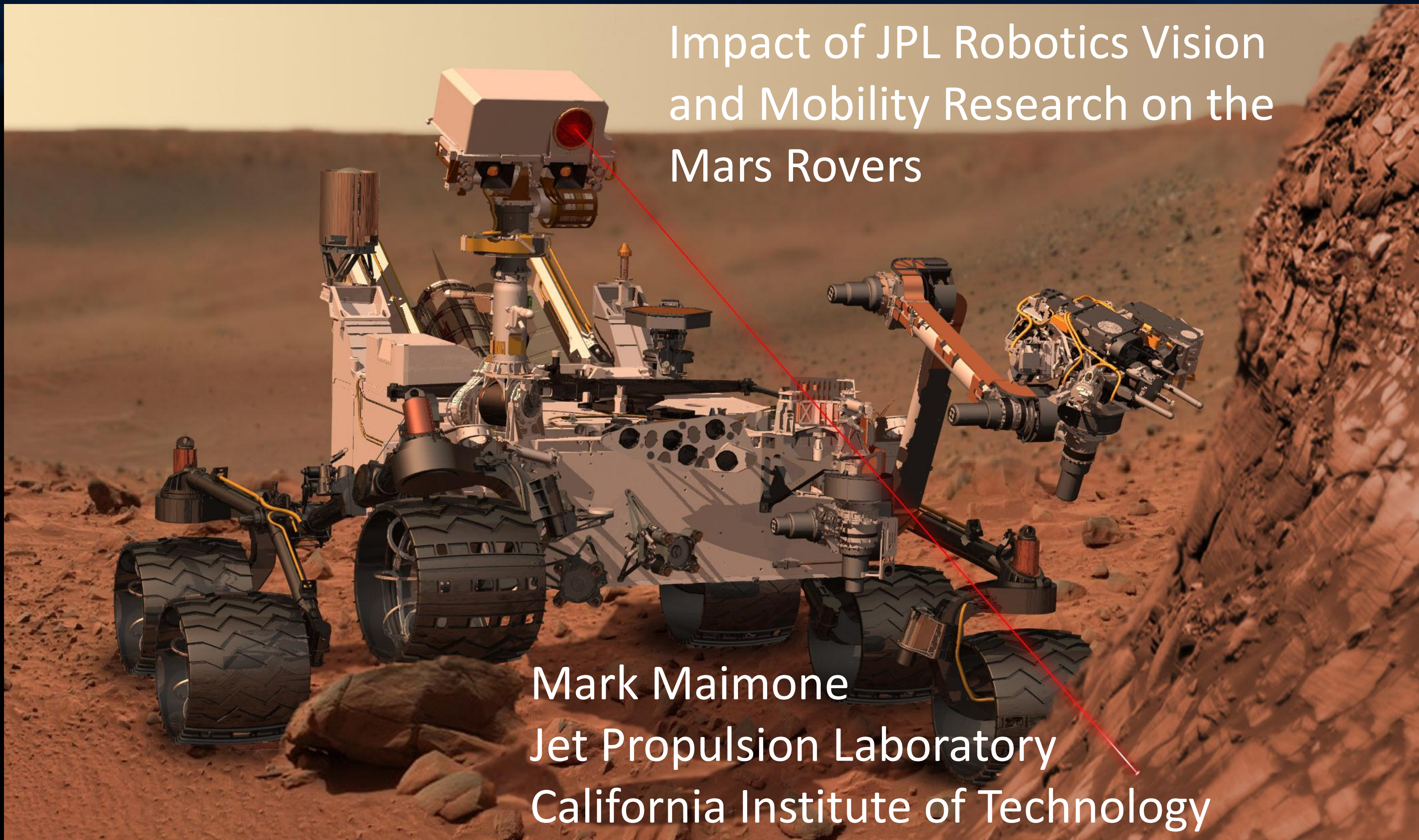
A Martian Vision:

Impact of JPL Robotics Vision and Mobility Research on the Mars Rovers

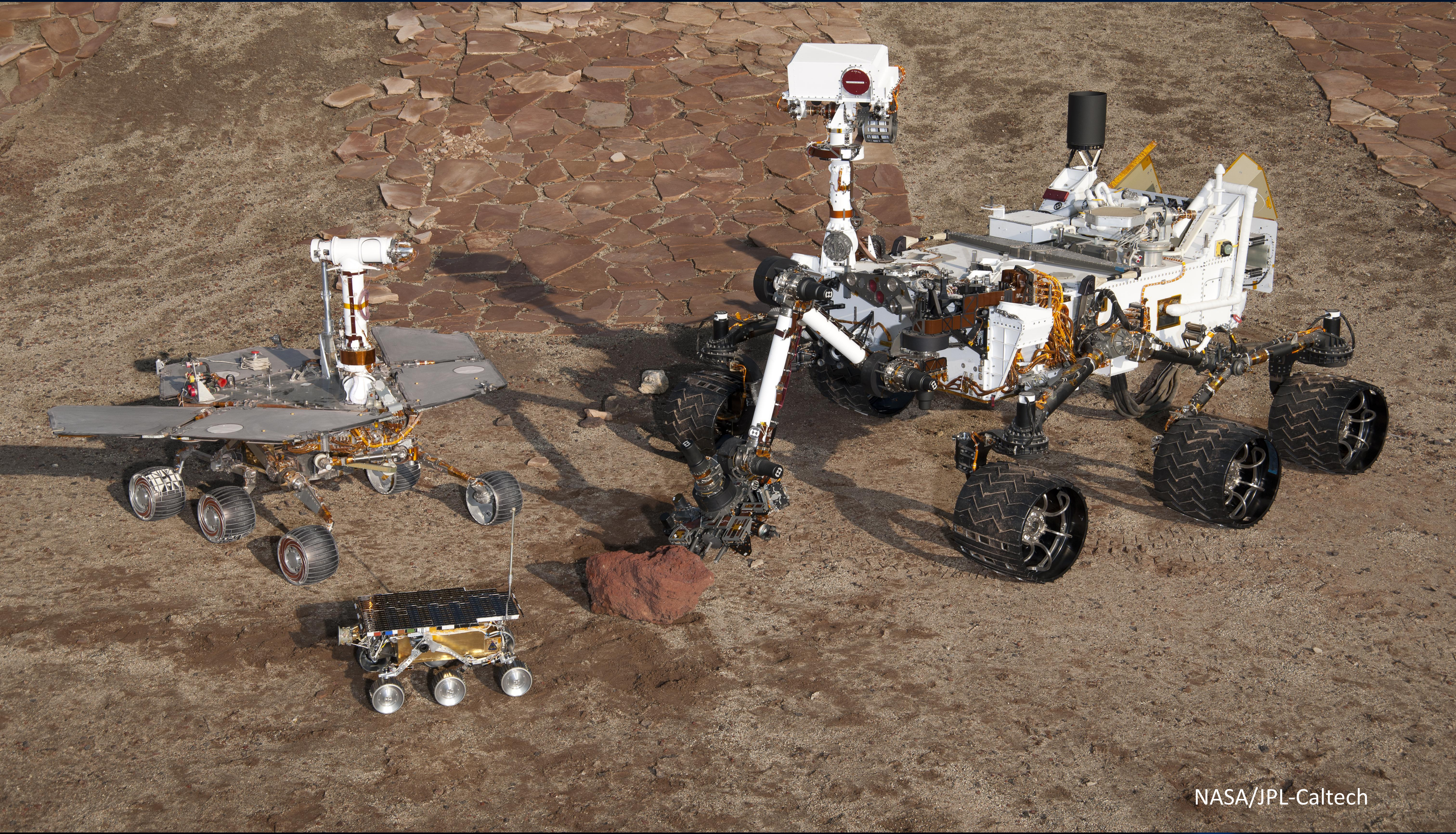
Mark Maimone
Jet Propulsion Laboratory
California Institute of Technology



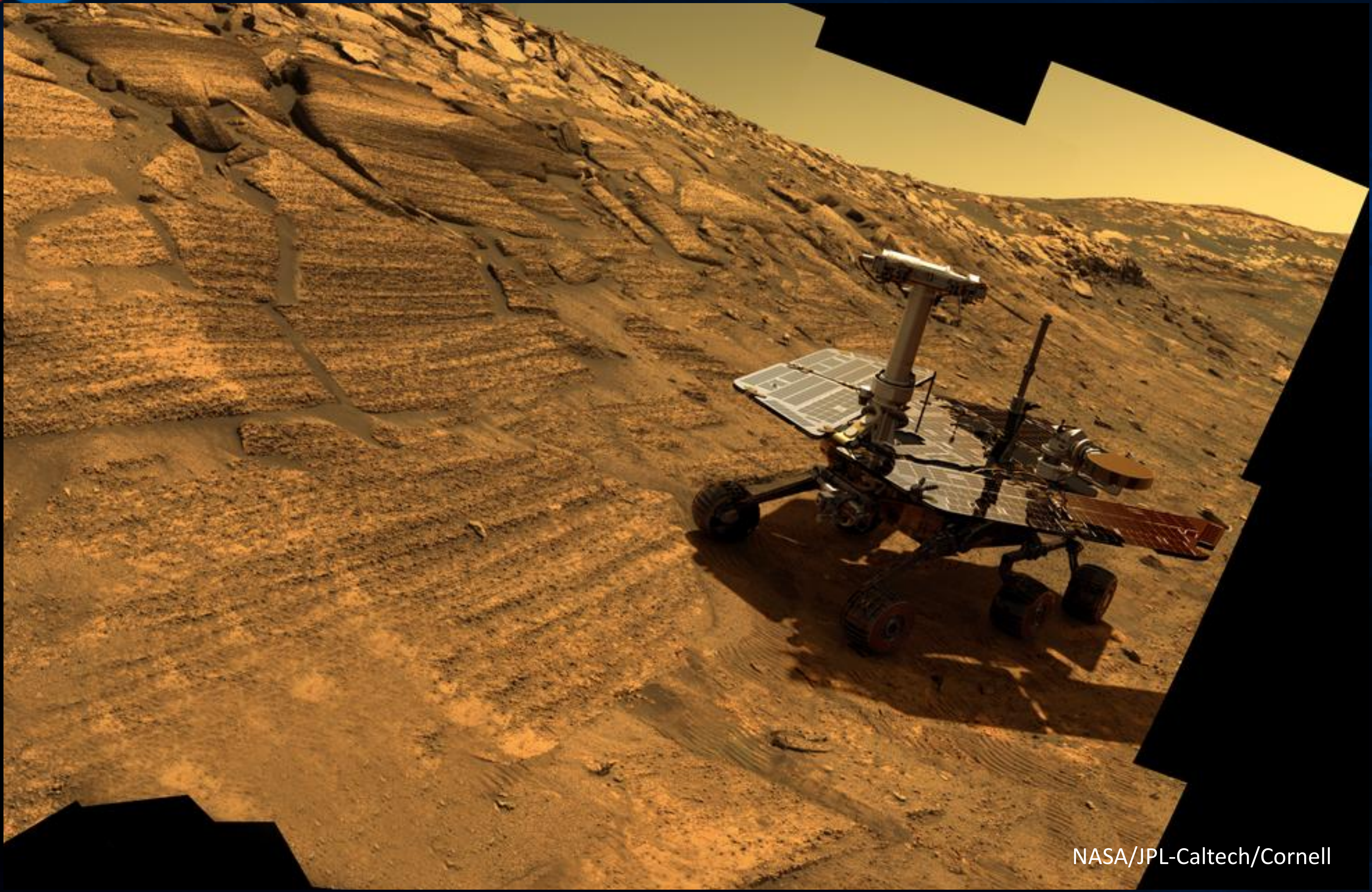
Artist's Concept. NASA/JPL-Caltech

Section 347 Senior Staff Lecture

Mars Rover Family Portrait



Mars Rovers Explore Slopes



And Craters

NASA/JPL/Cornell

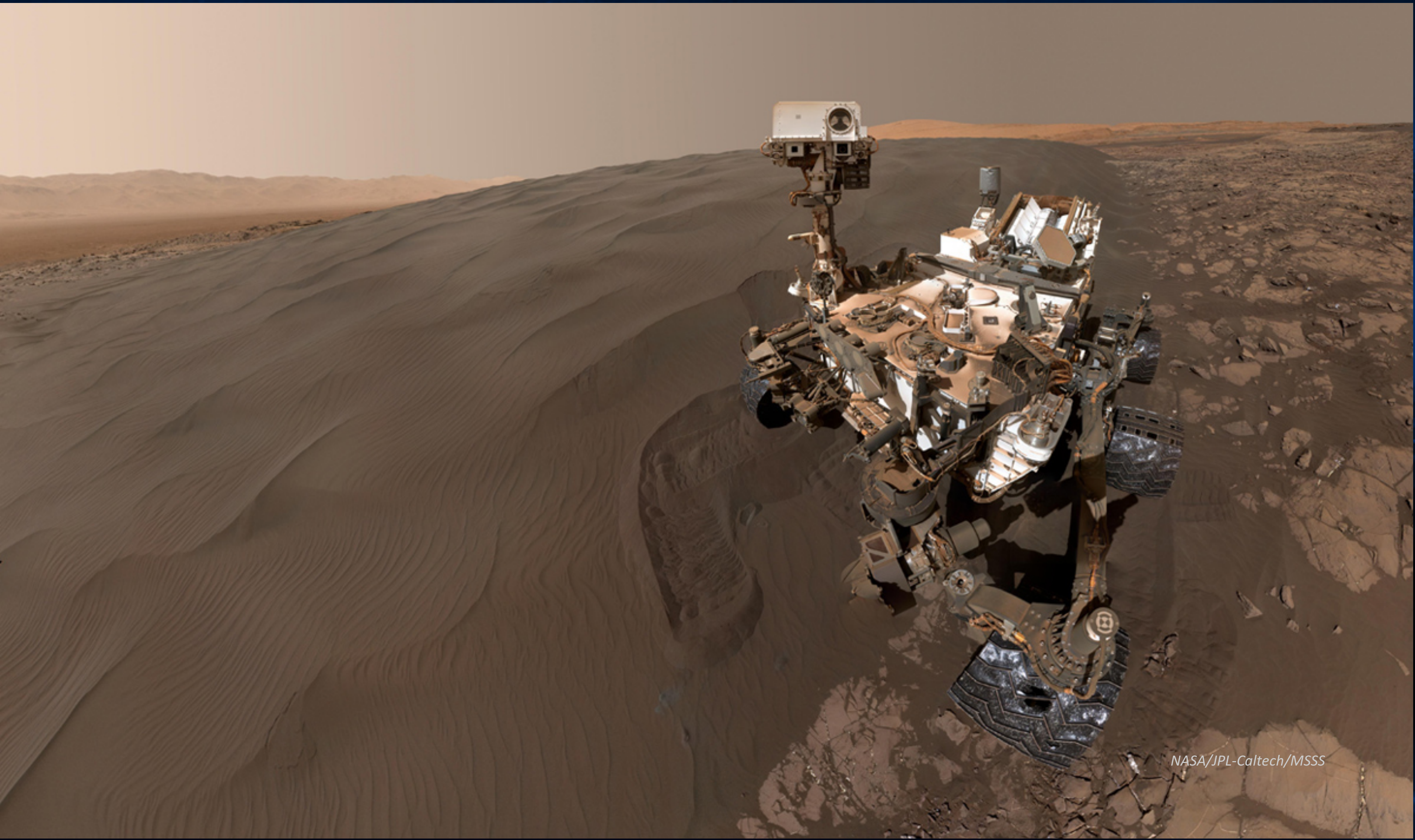
And Mountains

And Discover Buried Treasure

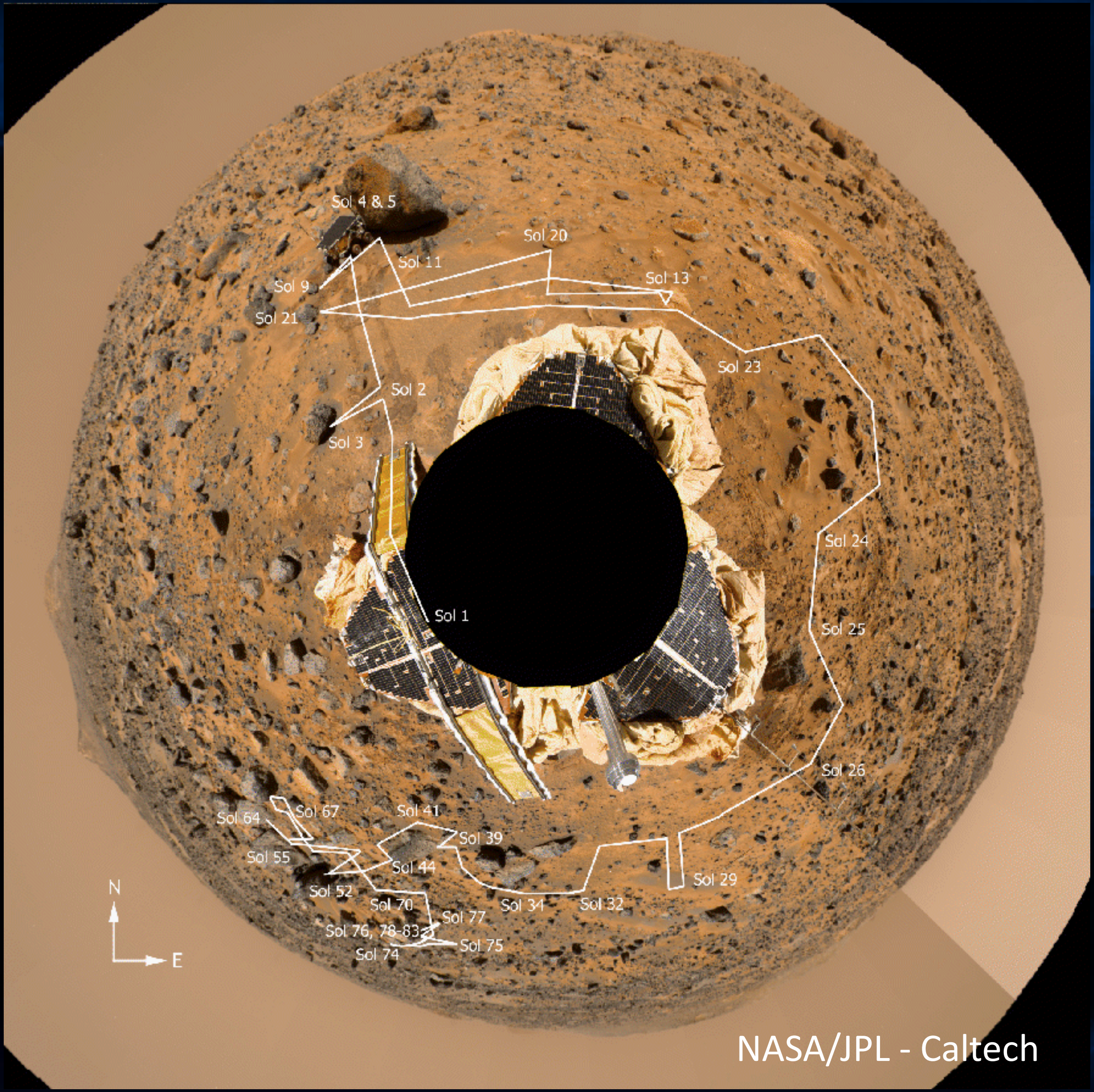
NASA/JPL-Caltech/Cornell

And Overcome Obstacles

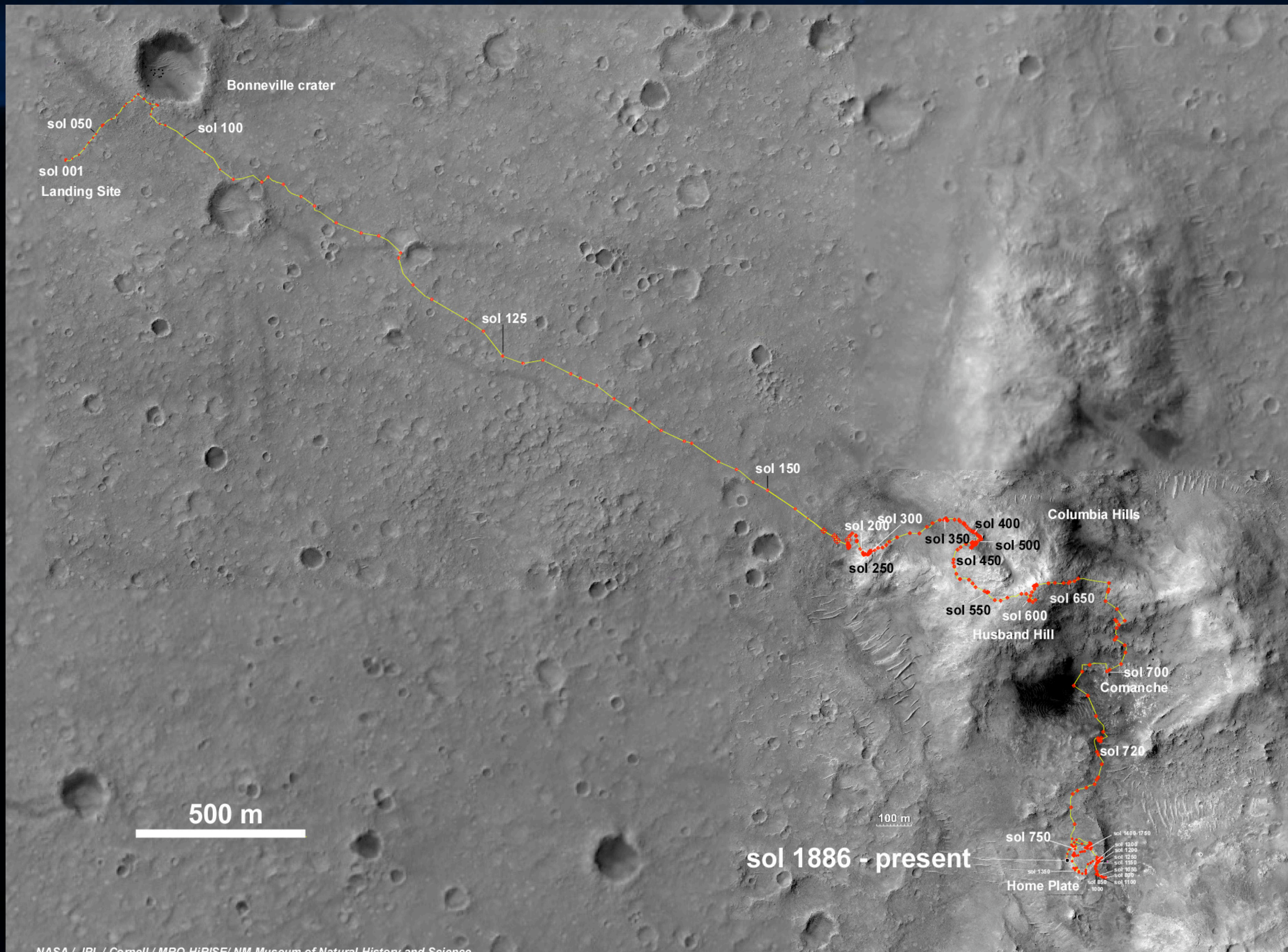
And Explore Novel Terrains



Sojourner drove 0.1 km in 0.3 years

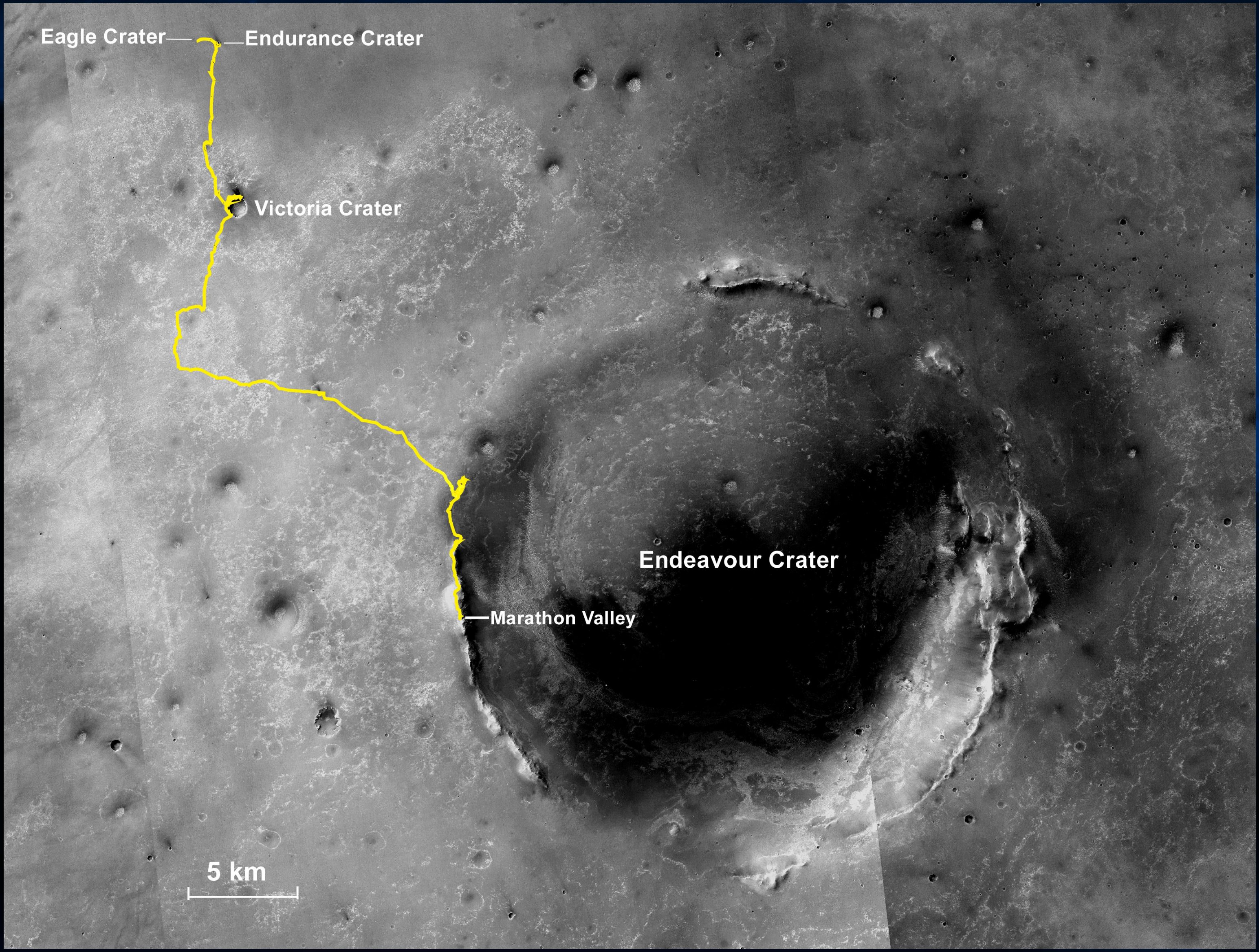


Spirit Drove 7.7 km in 6 years



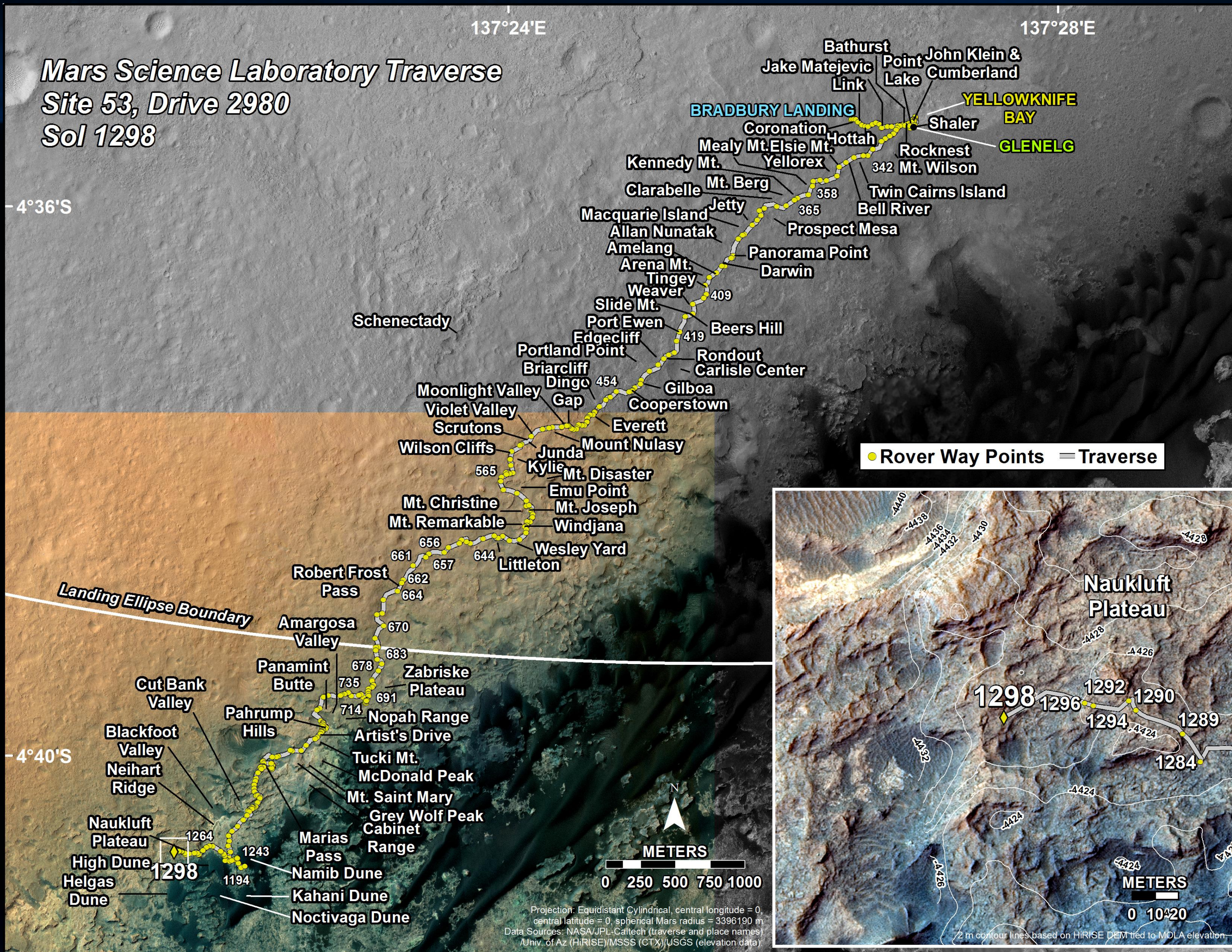
http://marsrovers.nasa.gov/mission/tm-spirit-all.html

Opportunity Drove 43 km in 12.3 years



http://marsmobile.jpl.nasa.gov/multimedia/images/?ImageID=7009

Curiosity Drove 13 km in 3.7 years



Section 347 Senior Staff Lecture

http://mars.jpl.nasa.gov/msl/multimedia/images/?ImageID=7786

Flight Rover Specs

	Sojourner	MER	MSL
CPU	80C85	BAE RAD6000	BAE RAD750
MHz	2	20	133
RAM (Mbytes)	0.56	128	512
Non-volatile storage (Mbytes)	0.17	256 flash	4,096 flash
Stereo Pixels processed per step	20	10,000 - 50,000	40,000 - 200,000

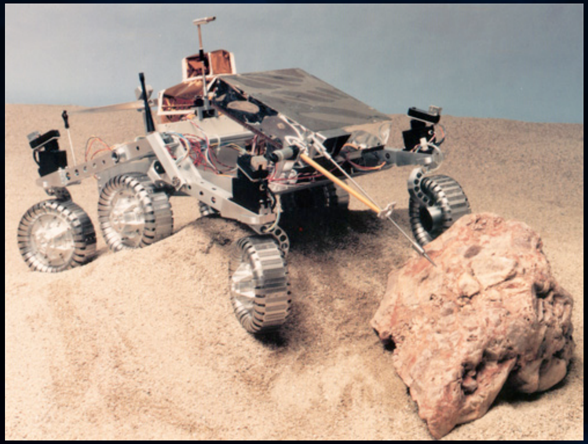
How Did We Get Here?

Research Rovers Go Way Back

SLRV (1964) (JPL and GM)

Blue Rover (1986)

Robby (1990)

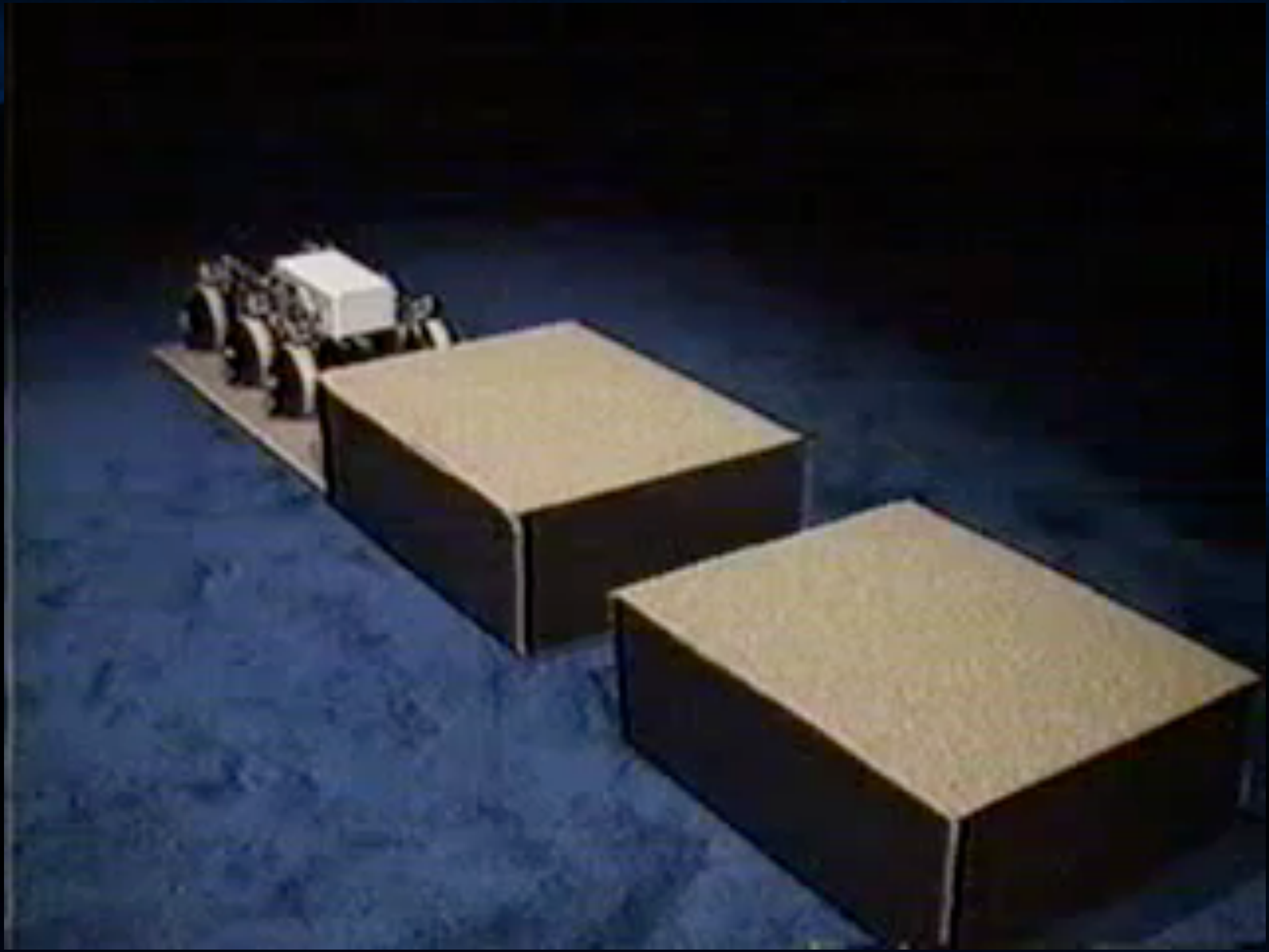


Rocky 4 (1992)

NASA/JPL-Caltech

Courtesy Issa Nesnas

Early Rocker/Bogie Prototype



Courtesy Brian Wilcox

Blue Rover

Courtesy Brian Wilcox

Robby

Courtesy Brian Wilcox

HMMWV

Courtesy Brian Wilcox

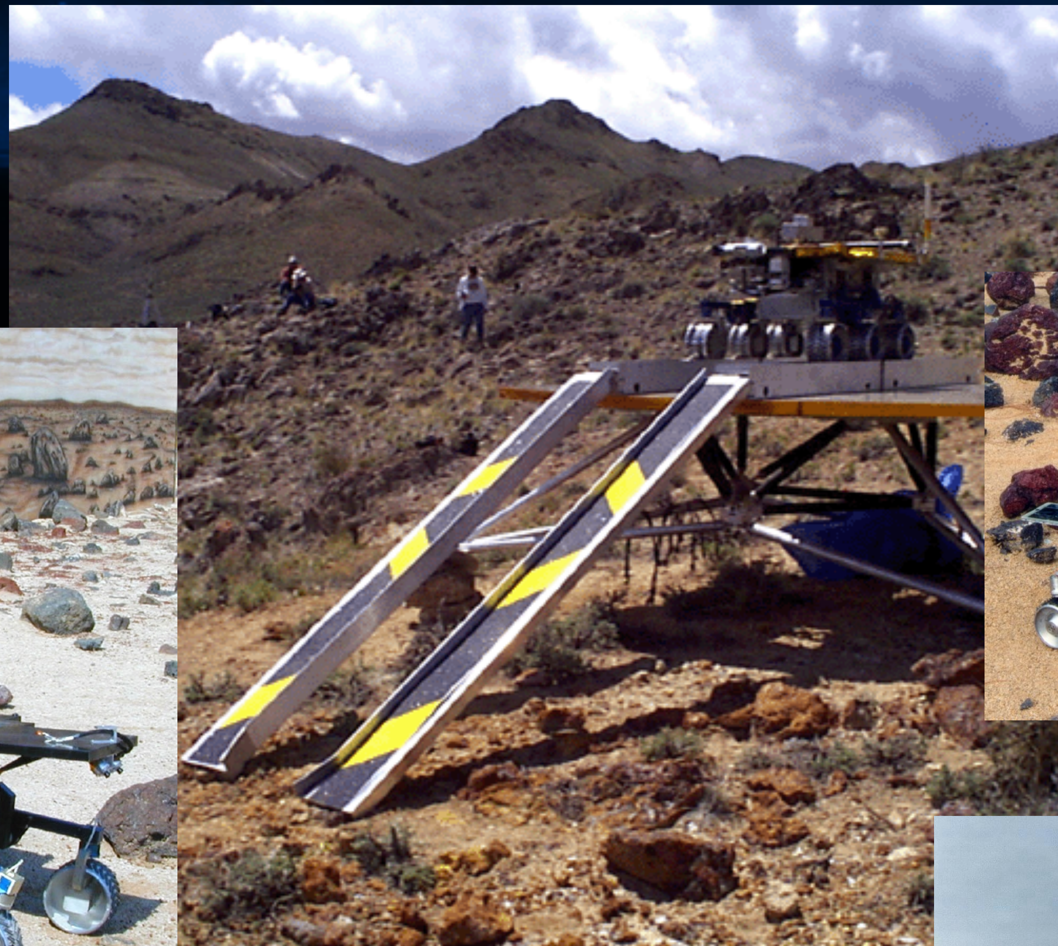
Rocky 3 Laser Stripe

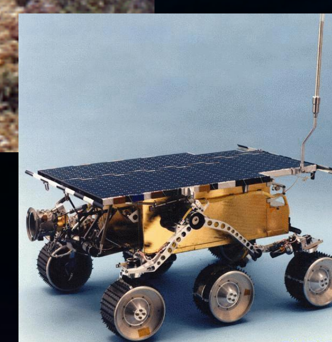
Courtesy Brian Wilcox

Rocky 4

Courtesy Brian Wilcox

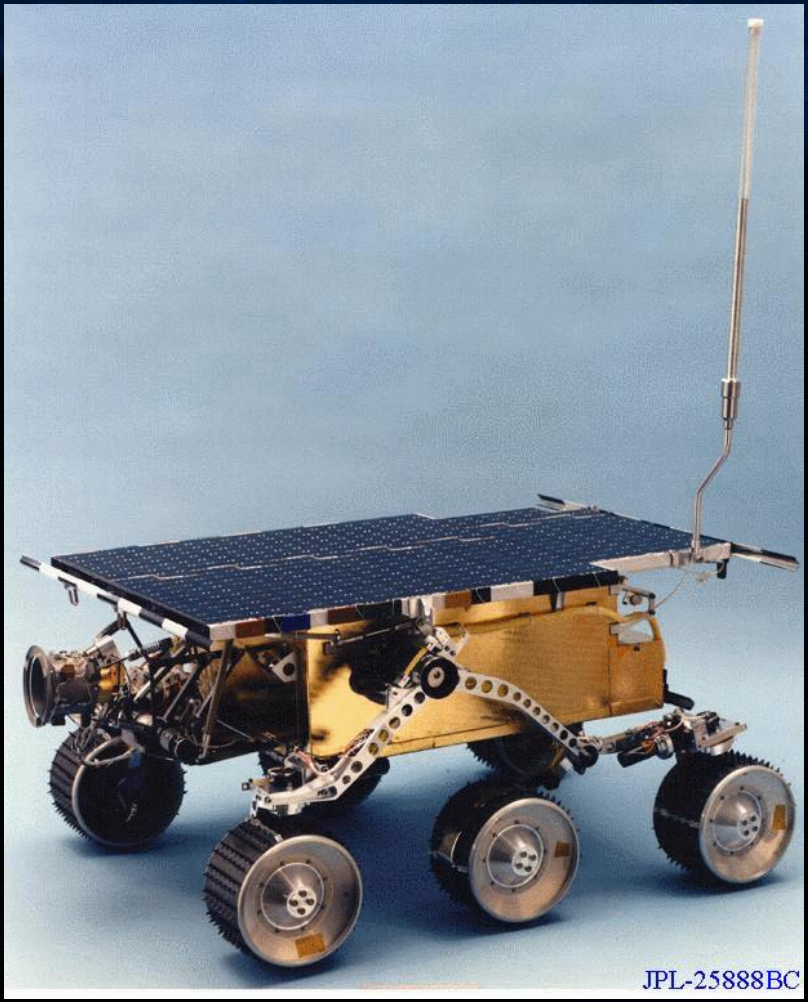
Rovers in 2001





NASA/JPL-Caltech

Sojourner / Marie Curie



NASA/JPL-Caltech

Developed by JPL (1994 - 1997) for Mars mission

After successfully arriving at Mars on 4 July 1997, Sojourner acquired images and analyzed rocks for nearly three months

A cousin of Rocky 7, Sojourner derives its design from the Rocky 4 prototype

Driven for a *total distance* of around 100 meters during its lifetime on Mars

Rocky 7

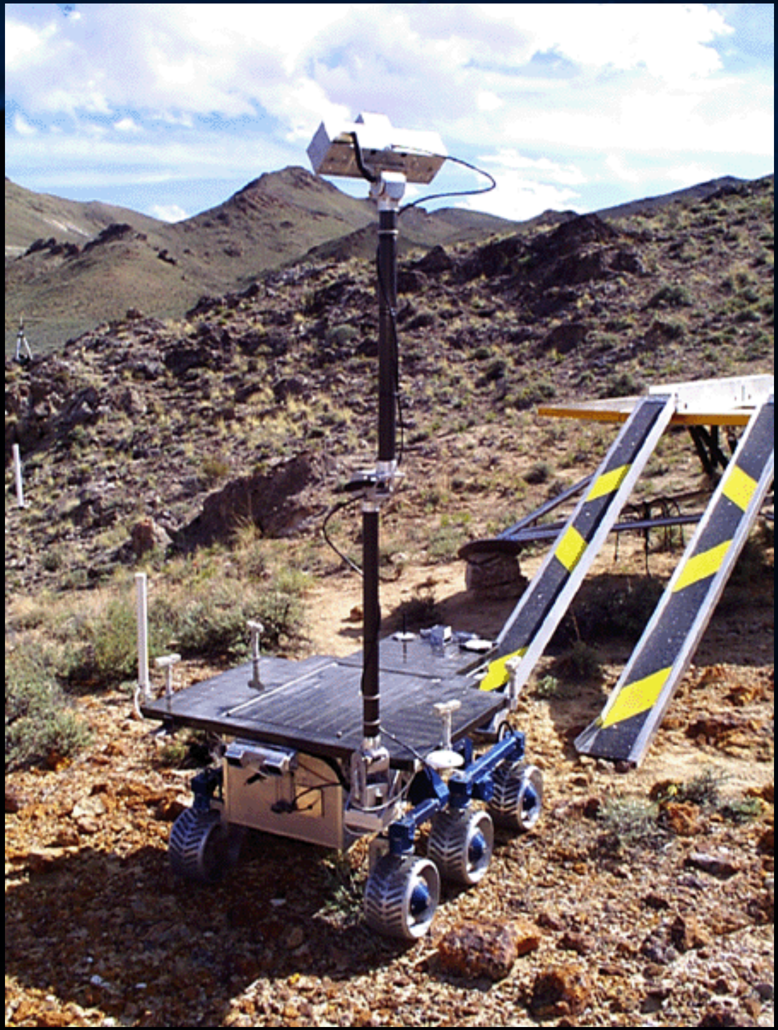
NASA/JPL-Caltech

Developed by JPL (1996-2001+) for long (> 10m) traverses

Rocker-bogey suspension

Includes two manipulators: extendible mast, sampling arm

FIDO



NASA/JPL-Caltech

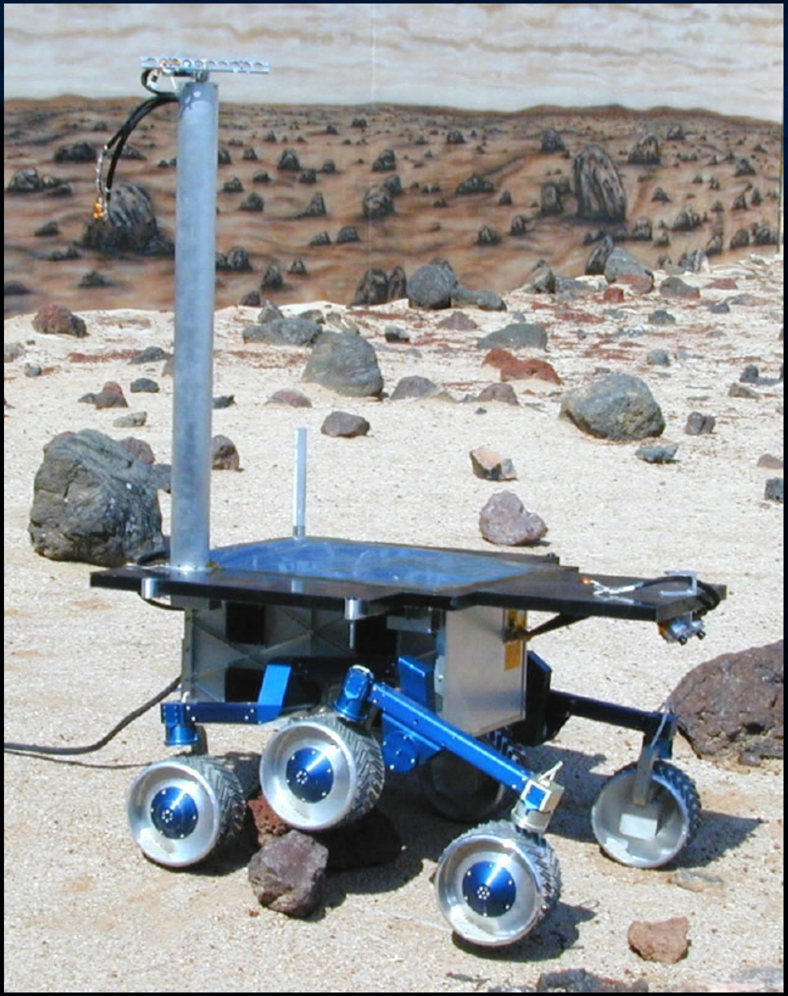
Developed by JPL (1998 – 2001+) for field training of scientists, preparing for (postponed) Mars Sample/Return mission Concept

Rocker-bogey suspension

Includes extendible mast, coring drill

Automated return-to-lander capability

Athena Software Development Model



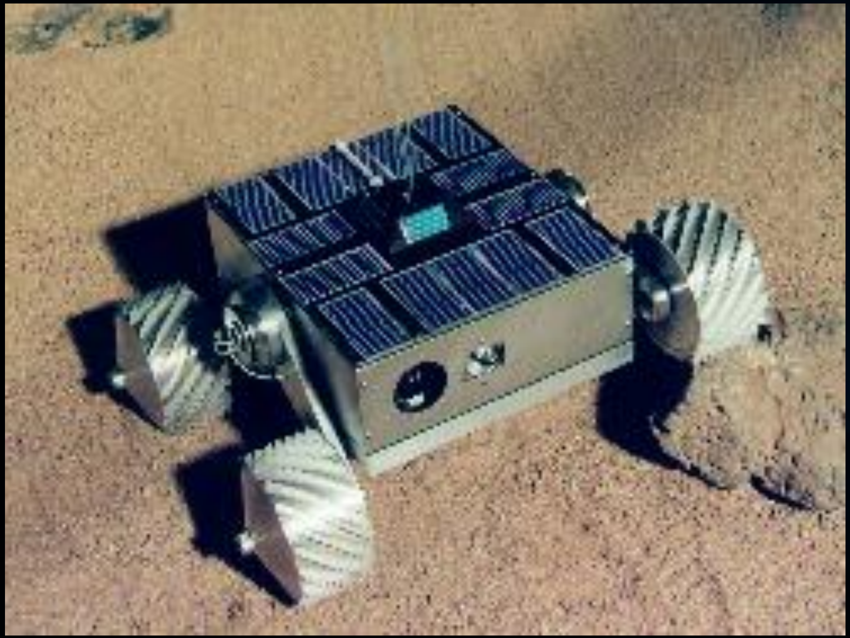
NASA/JPL-Caltech

Developed by JPL (1998 - 2000) as prototype for Mars Sample Return rover Concept

Uses FIDO chassis, but with spaceflight-equivalent electronics

Superceded by new requirements for 2003 Mars Exploration Rover

Nanorover



NASA/JPL-Caltech

Developed by JPL (1995 – 2001+) as research rover, thenpart of MUSES-C mission

4 wheels can move about central axis, enabling rover to self-right

Planned launch in 2002

Includes spectrometer and camera for science instruments

MUSES-CN rover being designed for microgravity environment

JPL Stereo Vision

Robotics Development: Rover Stereo Vision

Rover Stereo Vision

NASA - Planetary

US Army - TARDEC

Simultaneous, synergistic programs to develop navigation and control architectures for unmanned ground vehicles. The architectures were called "Computer-Aided Remote Driving (CARD) and Semi-Autonomous Navigation (SAN)

1987-1989

JPL – DDF
Algorithm breakthrough was achieved on 3-D perception with real-time stereo vision

1990

"Robby"
100M traverse by Mars rover testbed

1991-92

Robotics Tech Test Vehicle (RTTV)
Extended real-time stereo-vision for use in CARD for safe-guarded remote driving of HMMWV

1992-96

DARPA DEMO II
Further extension of stereo-vision for semi-autonomous, off road navigation of robotic HMMWVs in scout mission scenarios

1997

Mars Pathfinder
Fast mapping enabled of terrain around lander; mission planning critical

1997-2001

ARL DEMO III
Maintained core competency in real-time stereo vision for autonomous navigation

2003

MER
Stereo-vision is selected as sole 3-D sensor for rover mission. ***Evolved versions of software remains essential for MSL and Mars2020***

NASA/JPL-Caltech

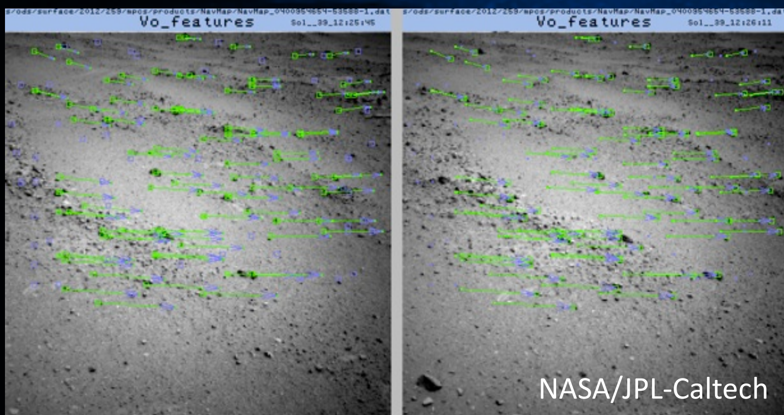
1

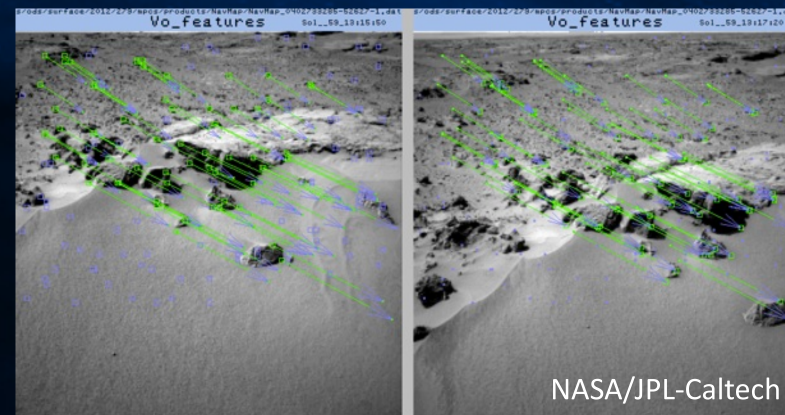
Courtesy Larry Matthies

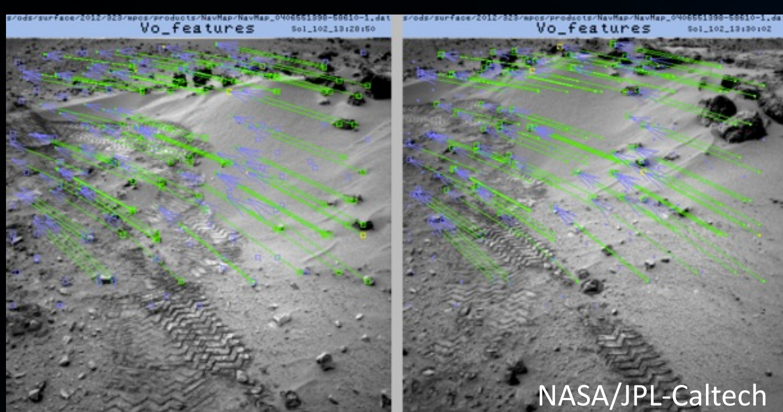
Robotics Tech used for Rovers

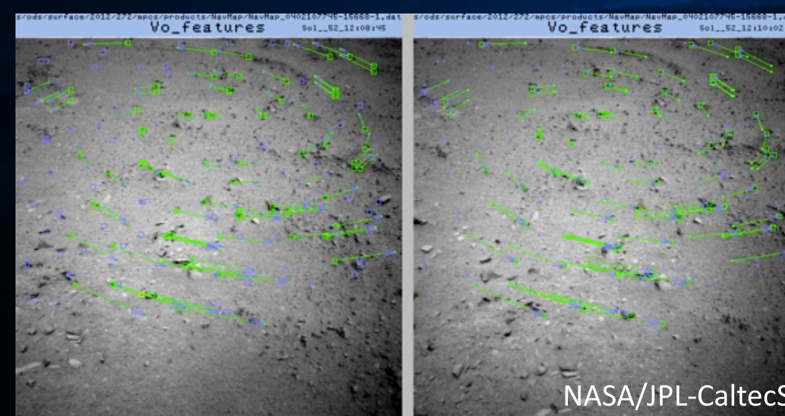
Visual Odometry, Slip Checks, VO Auto
Dense Stereo Vision
Autonomous Terrain Assessment
AutoNav and Guarded Driving
Local and Global Waypoint Planning
Multi-sol Driving
Visual Target Tracking
Simulation
Rover Sequencing and Visualization
Terrain Classification
Autonomous Image Interpretation for Science
Autonomous Fault Response
Velocity-controlled Driving
Precision Arm Placement
Percussive Drill
Cached Sample Manipulation
…

Using visual odometry, the rover constantly compares pairs of images of nearby terrain to calculate its position.







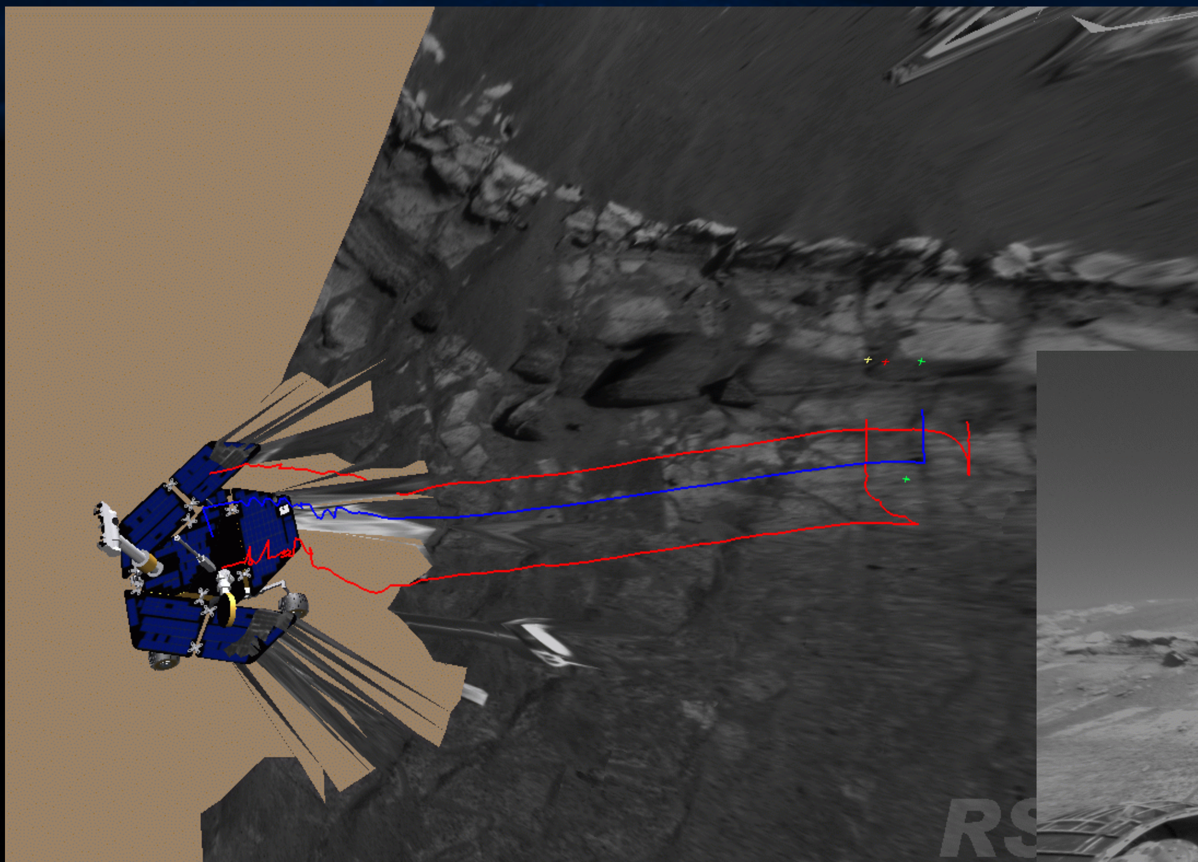


Unlike terrestrial robots, Curiosity drives as far as possible between VO images

Why We Need VO: Unpredictable Slip

Looking back at "Wopmay" and two weeks of challenging drives. Opportunity Sol 272

VO Enables Fewer Approach Sols



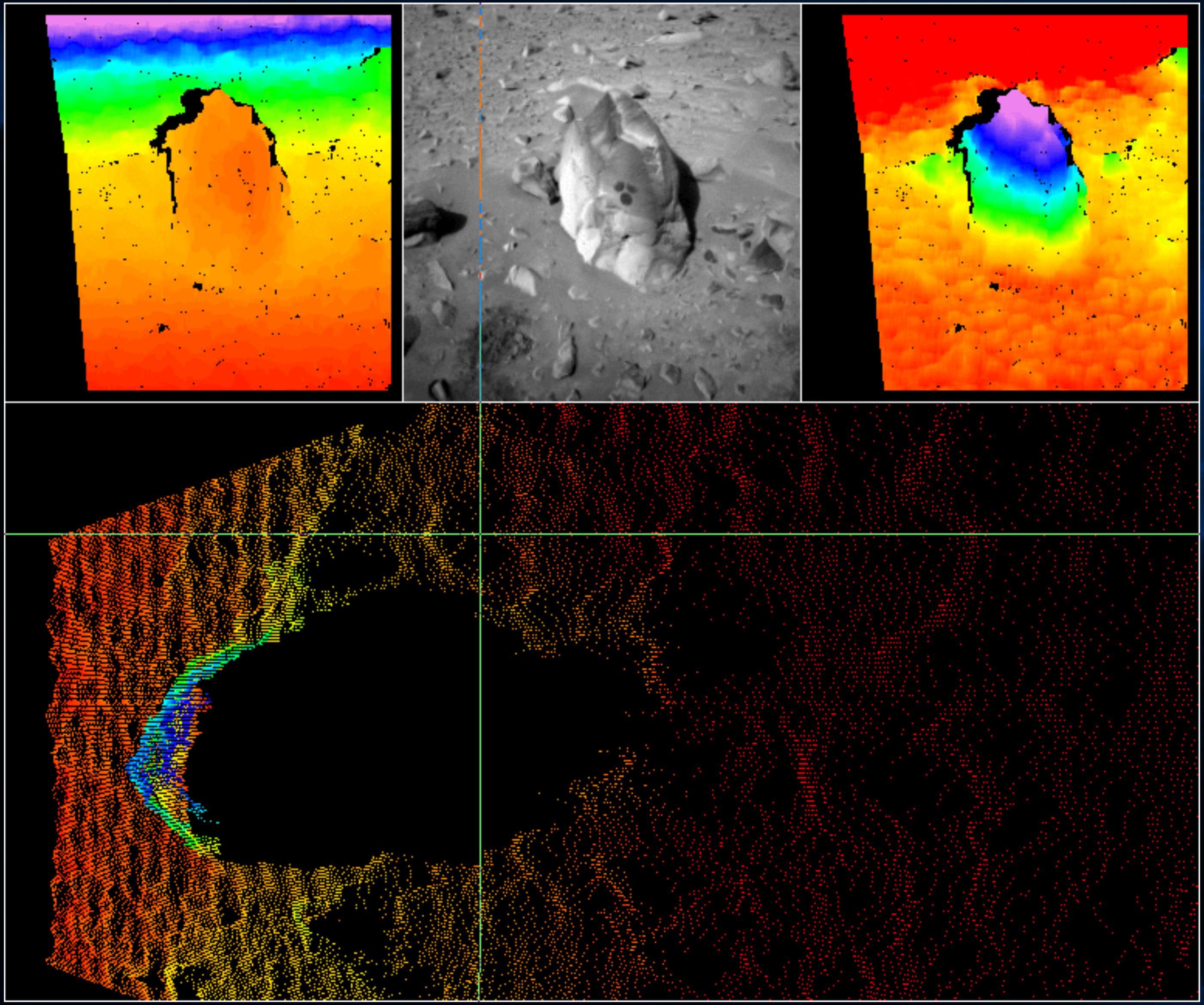
NASA/JPL-Caltech

VisOdom enabled 8 meter 1-sol approach on 20-24 degree slope

Visual Odometry Benefits

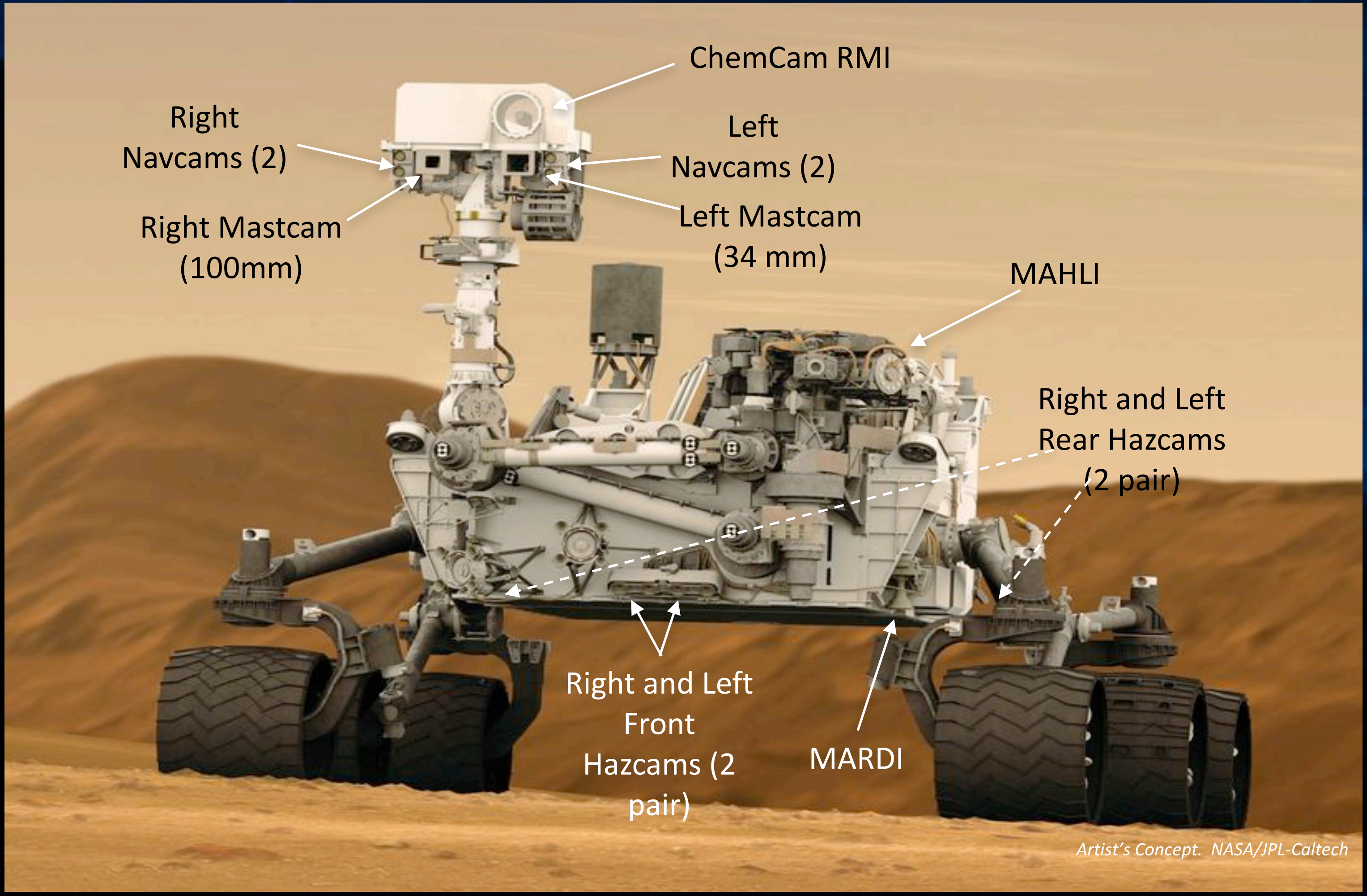
- Visual Odometry Increases Science Return
  - **Provides robust mid-drive pointing; even if you slip, the proper target can still be imaged**
  - **Enables difficult approaches to targets in fewer Sols; drive sequences conditional on position**
- Visual Odometry improves Rover Safety
  - **Keep-out zones; if you slide too close to known hazards, abort the drive**
  - **Slip checks; if you're not making enough forward process, abort the drive**

Onboard Dense Stereo: Spirit's Navcam



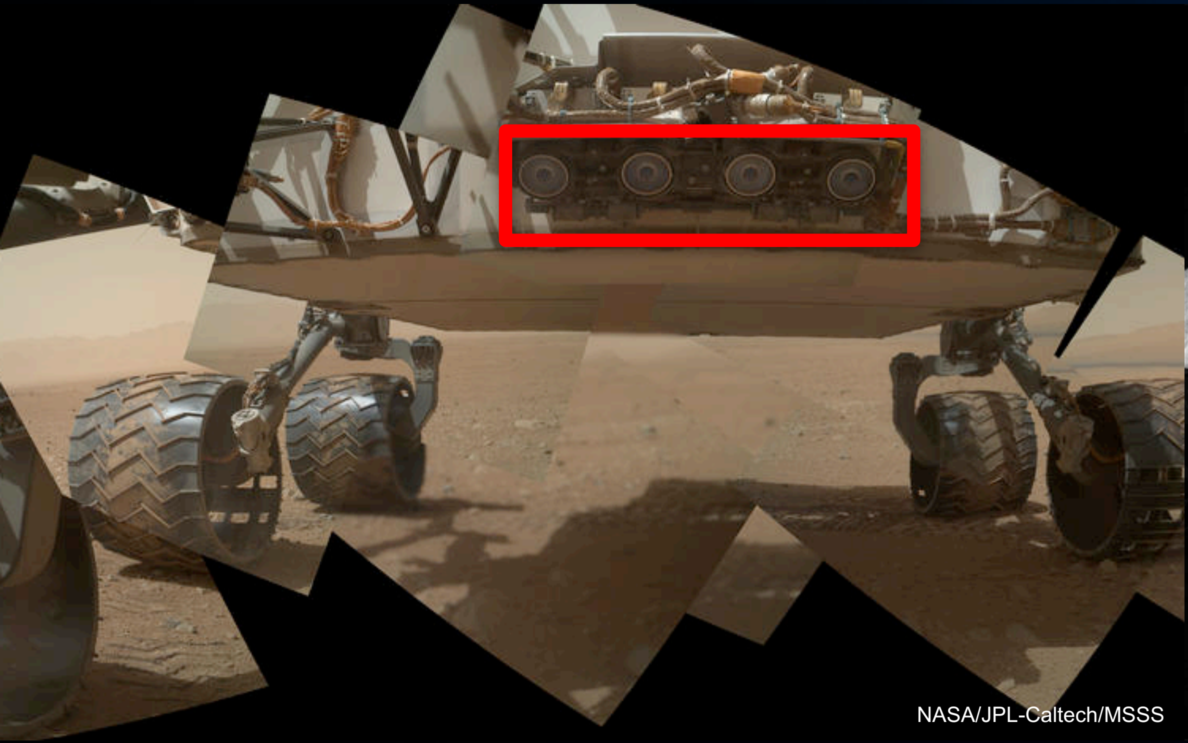
NASA/JPL-Caltech

Curiosity has 17 cameras

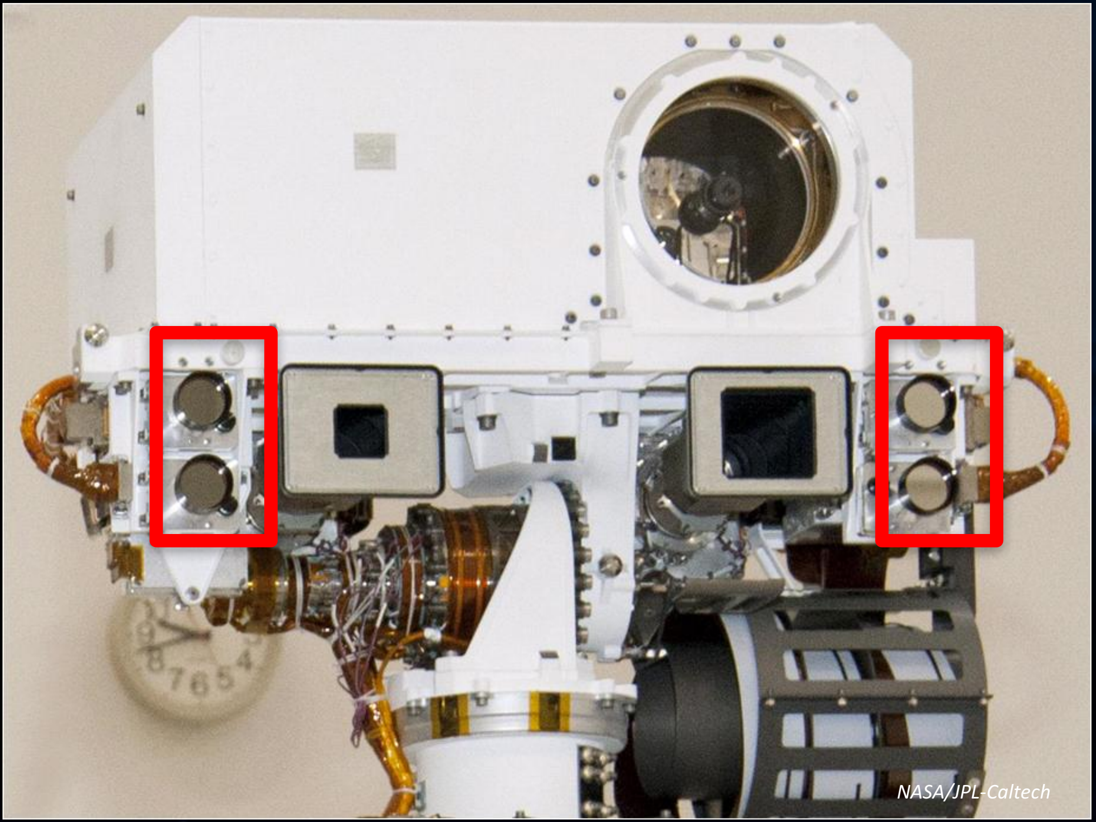


However, only the Hazcams and Navcams are tied into the auto-nav software.

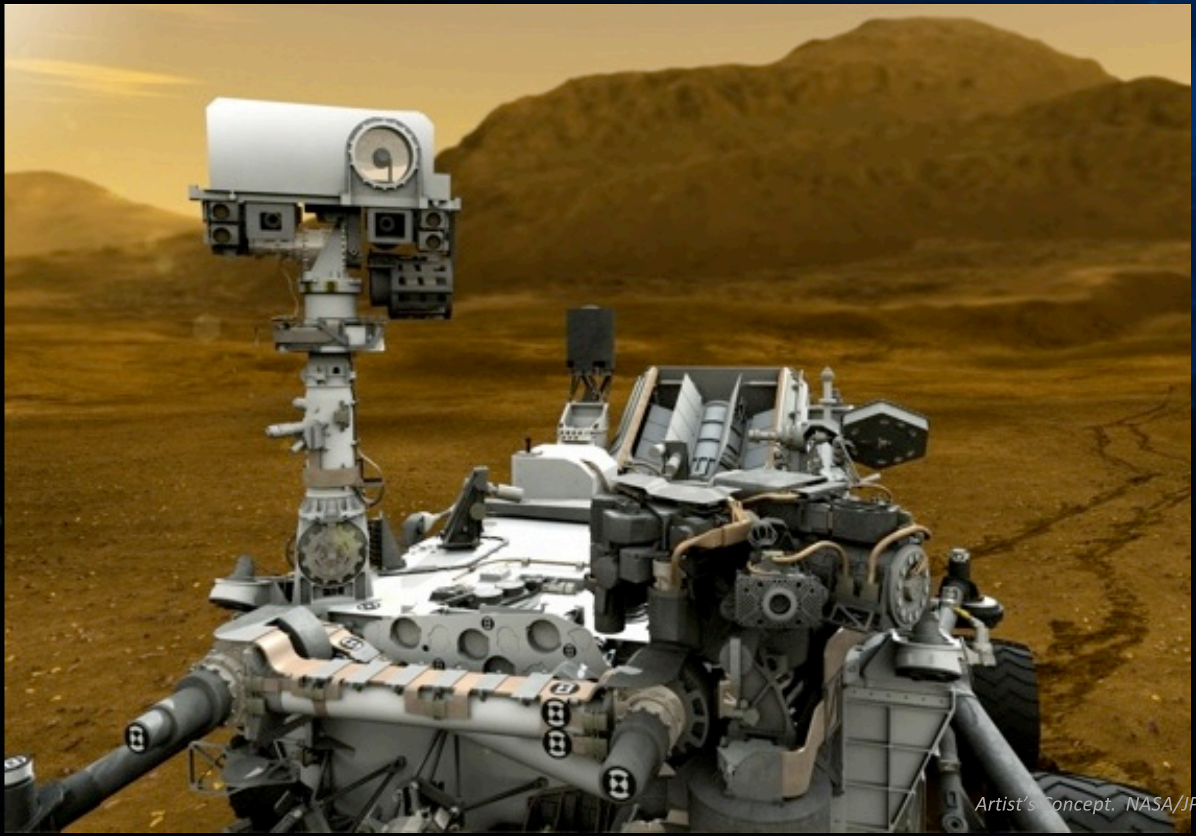
The hazard avoidance cameras give a 120° wide angle view of the area near the rover. Front cameras have 16cm baseline, rear cameras have 10cm baseline.



The 45° navigation cameras are almost 7 feet off the ground with 42cm baseline, providing good views over nearby obstacles or hills and into ditches.



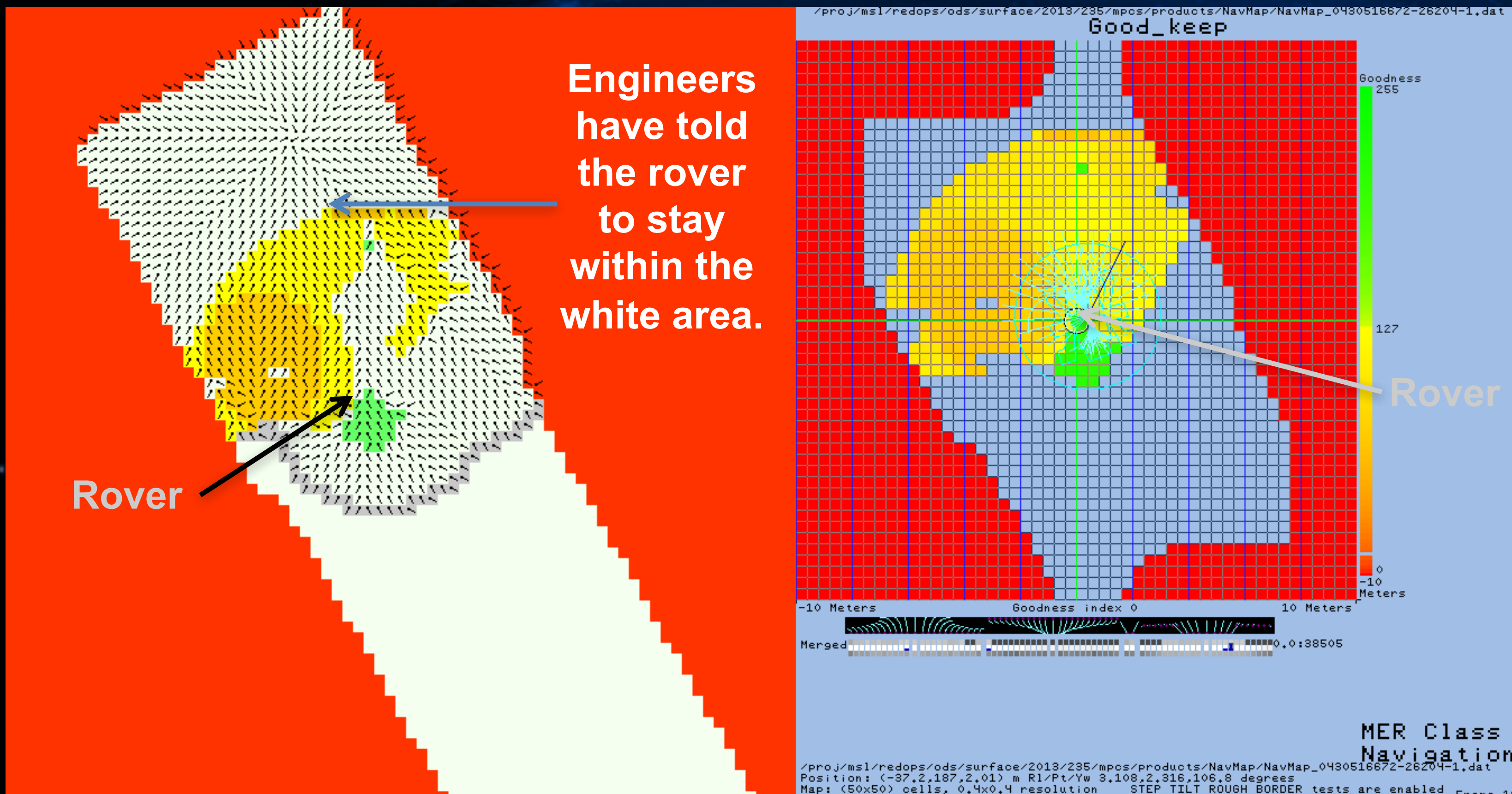
During nominal auto-nav, the rover stops every 0.5-1.5 meters, takes 4 sets of images, evaluates hazards, and then chooses where to drive.



Artist's Concept. NASA/JPL-Caltech

Auto-nav extends directed drives into previously unseen terrain

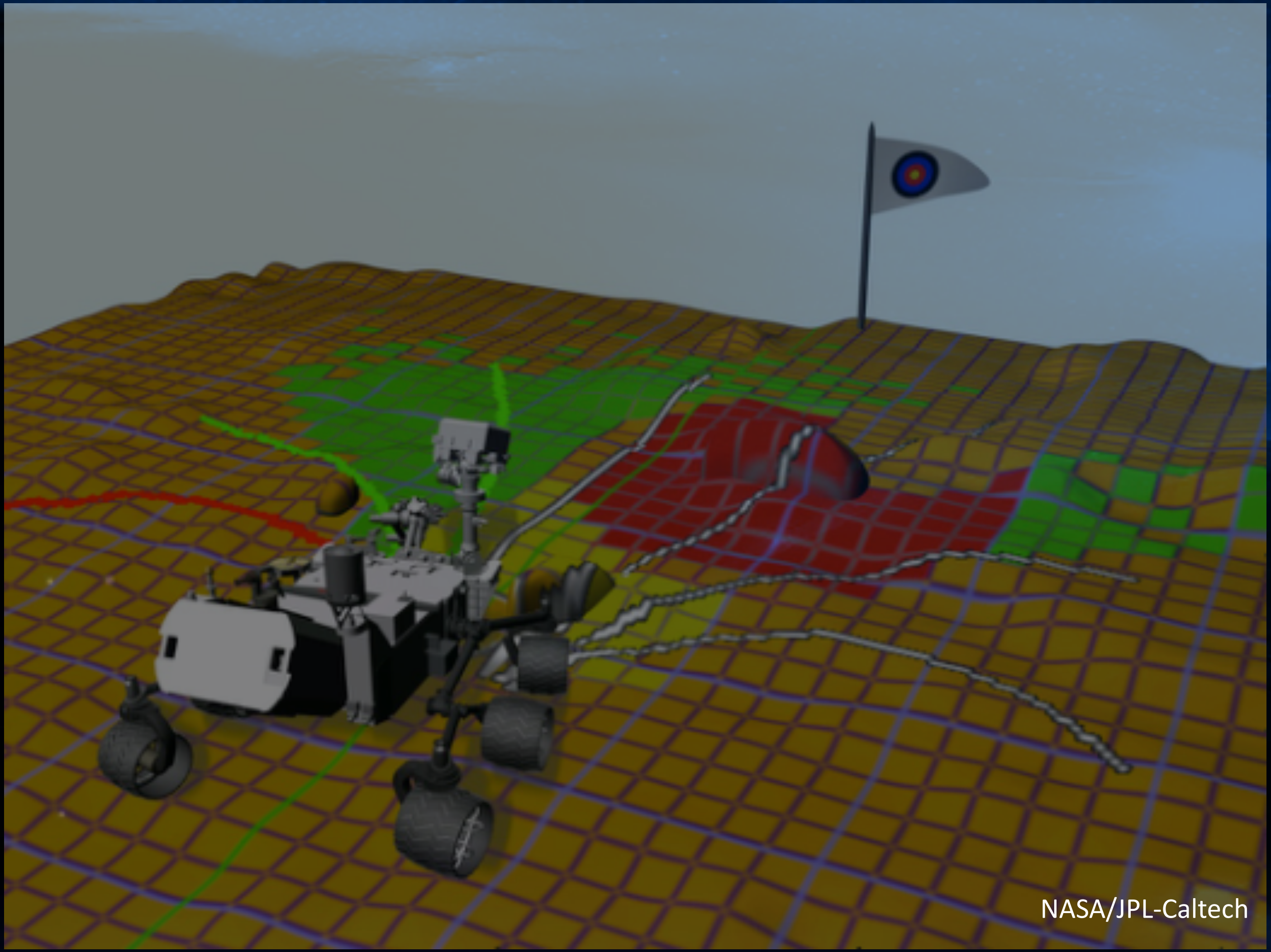
The rover reduces a stereo point cloud into a configuration space, labeling unsafe areas red and safe areas green.



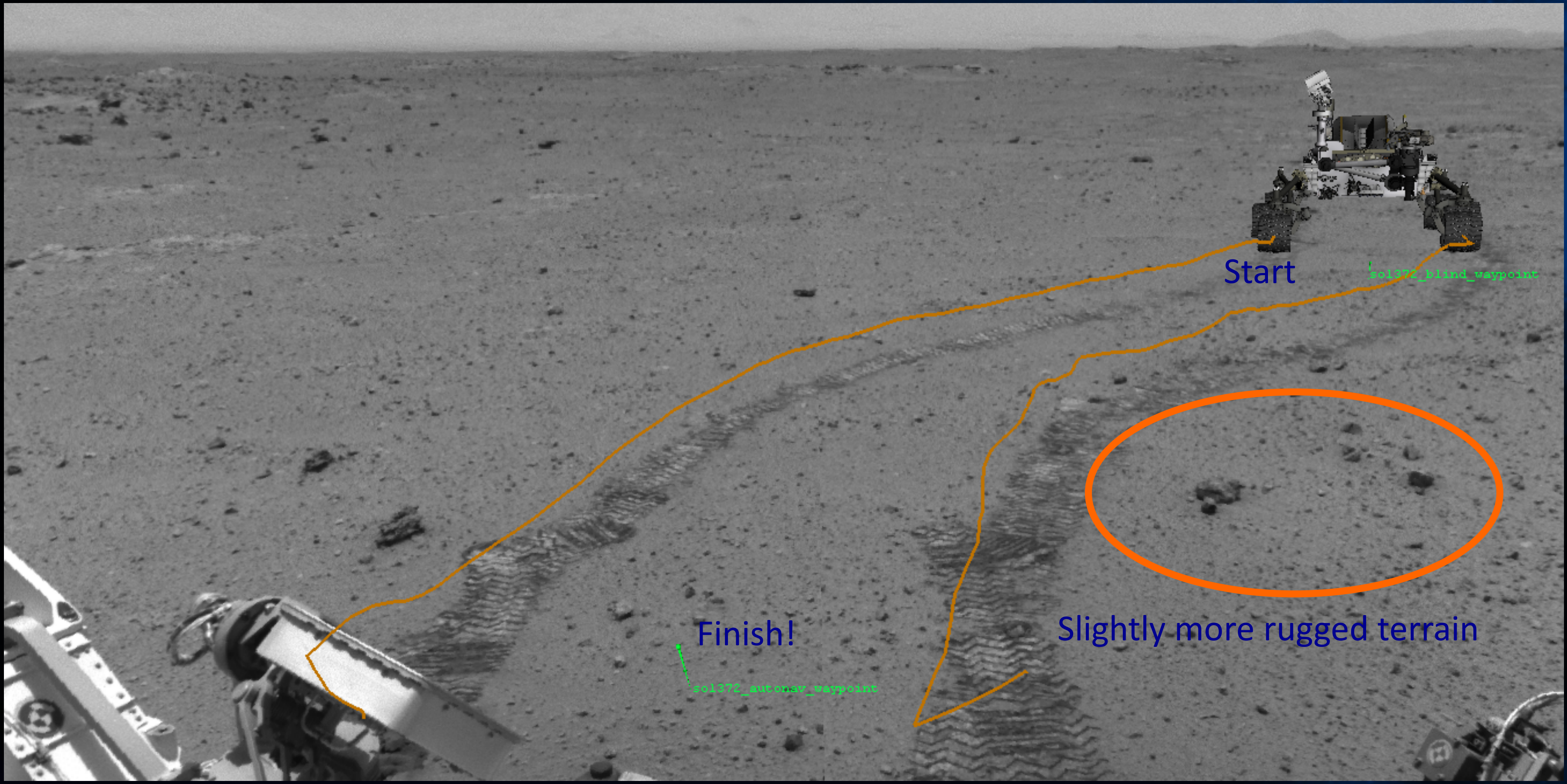
NASA/JPL-Caltech

Yellow means drive carefully, just like on Earth.

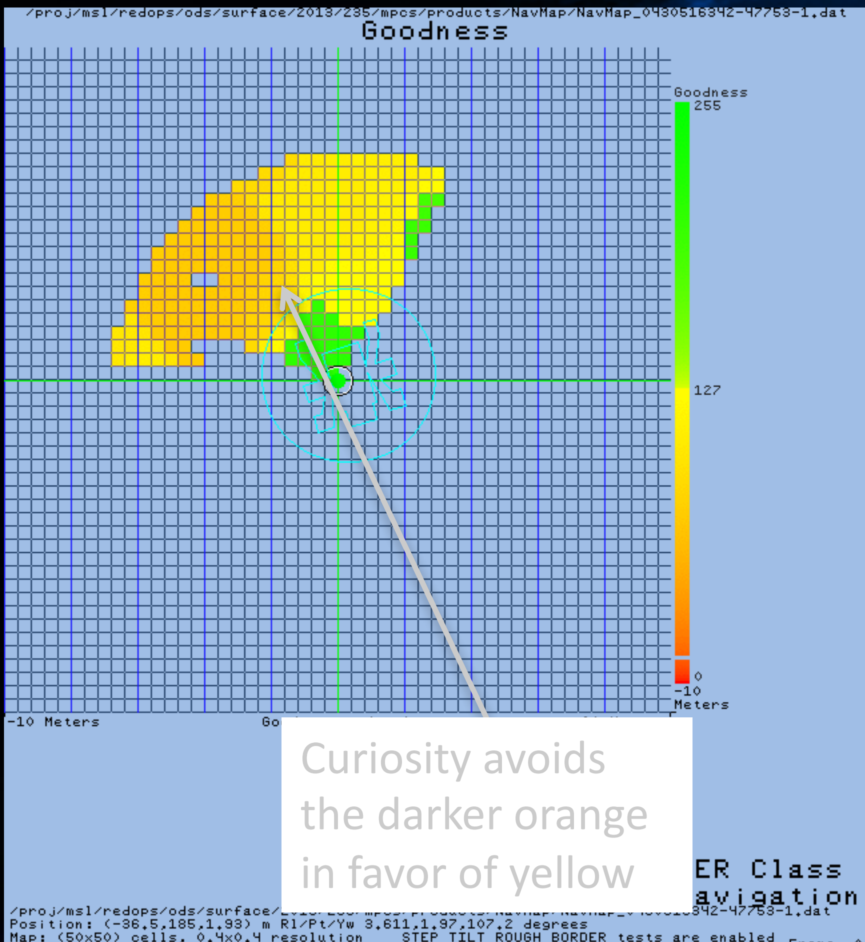
Watch "Rover Navigation 101" online for deets.



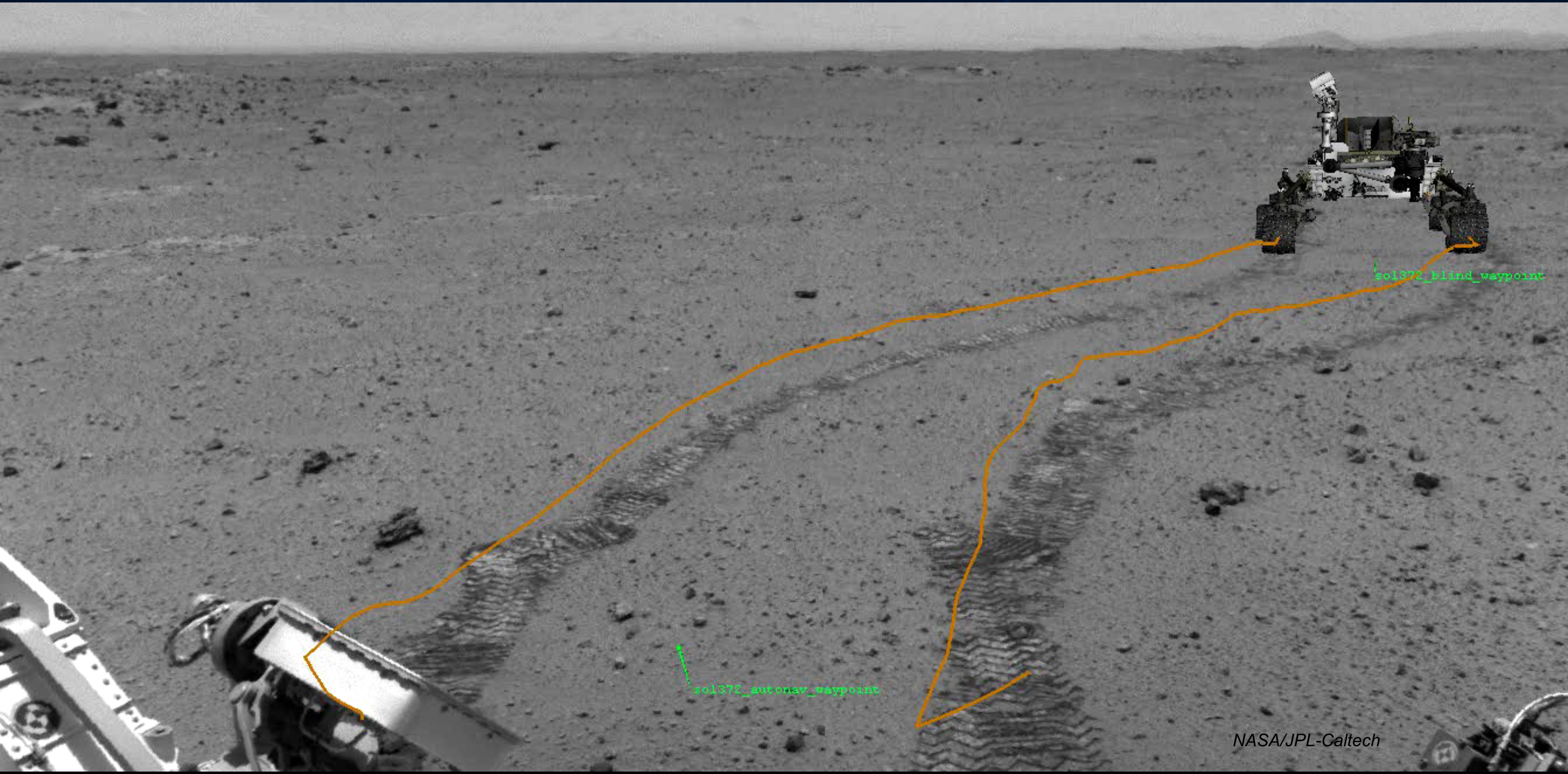
Wheel tracks after the first auto-nav drive on sol 372 show that Curiosity chose to drive around a little mound of loose rock.



Curiosity's map and tracks show this decision to turn was based on her evaluation of the terrain.



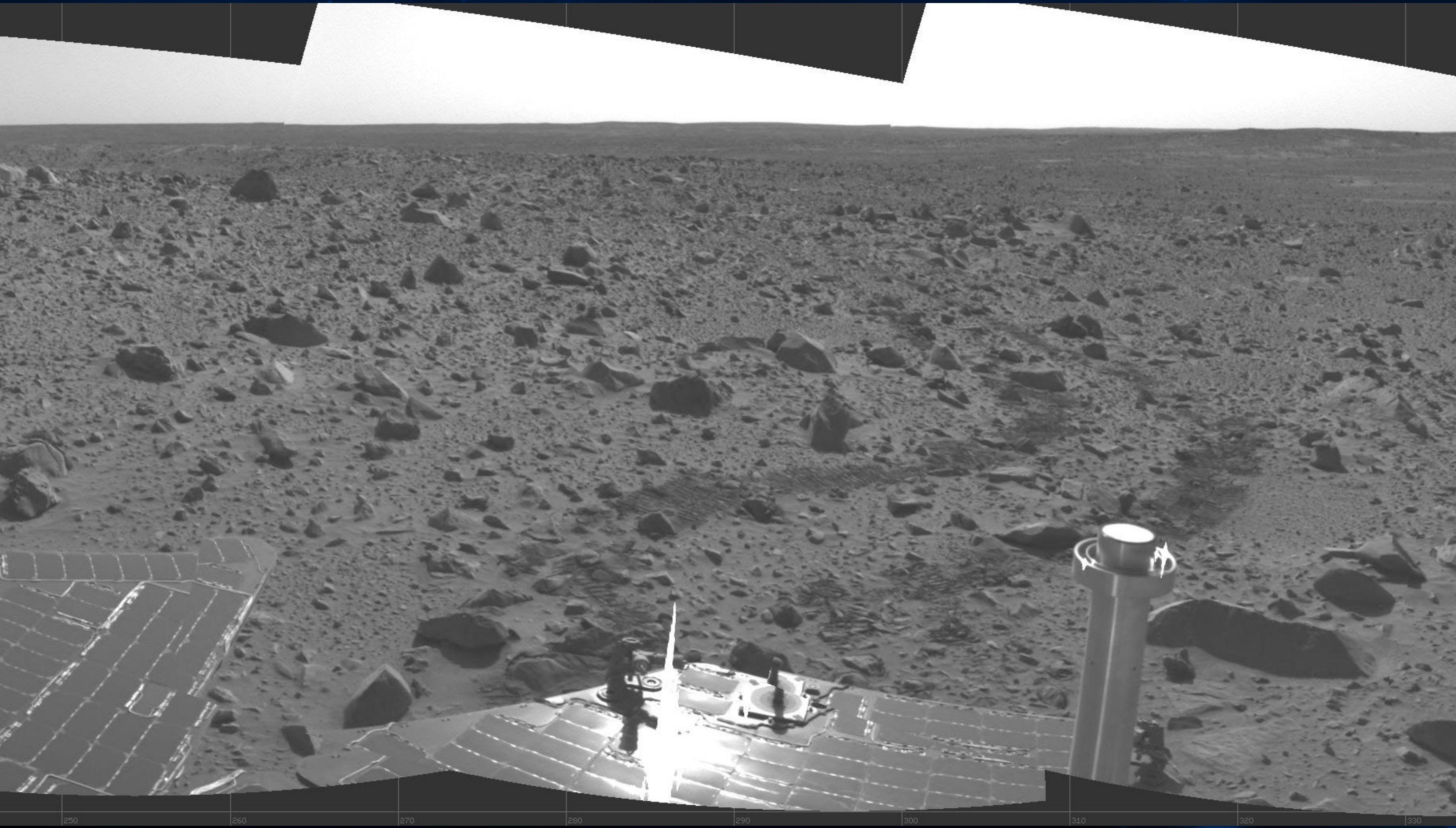
Animation of Curiosity's actual Sol 372 drive over a picture of her tracks



Finish!

Spirit Sol 106: Avoiding a 21cm rock

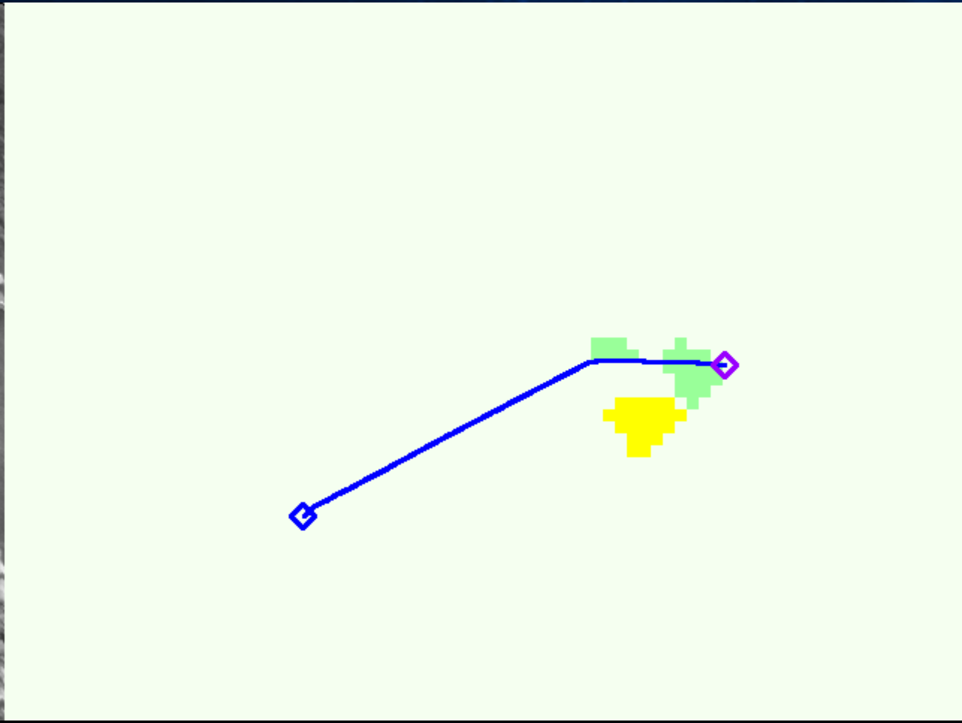
Spirit Sol 107: Avoiding Rock Pile



NASA/JPL-Caltech

D* Global Planner in the lab

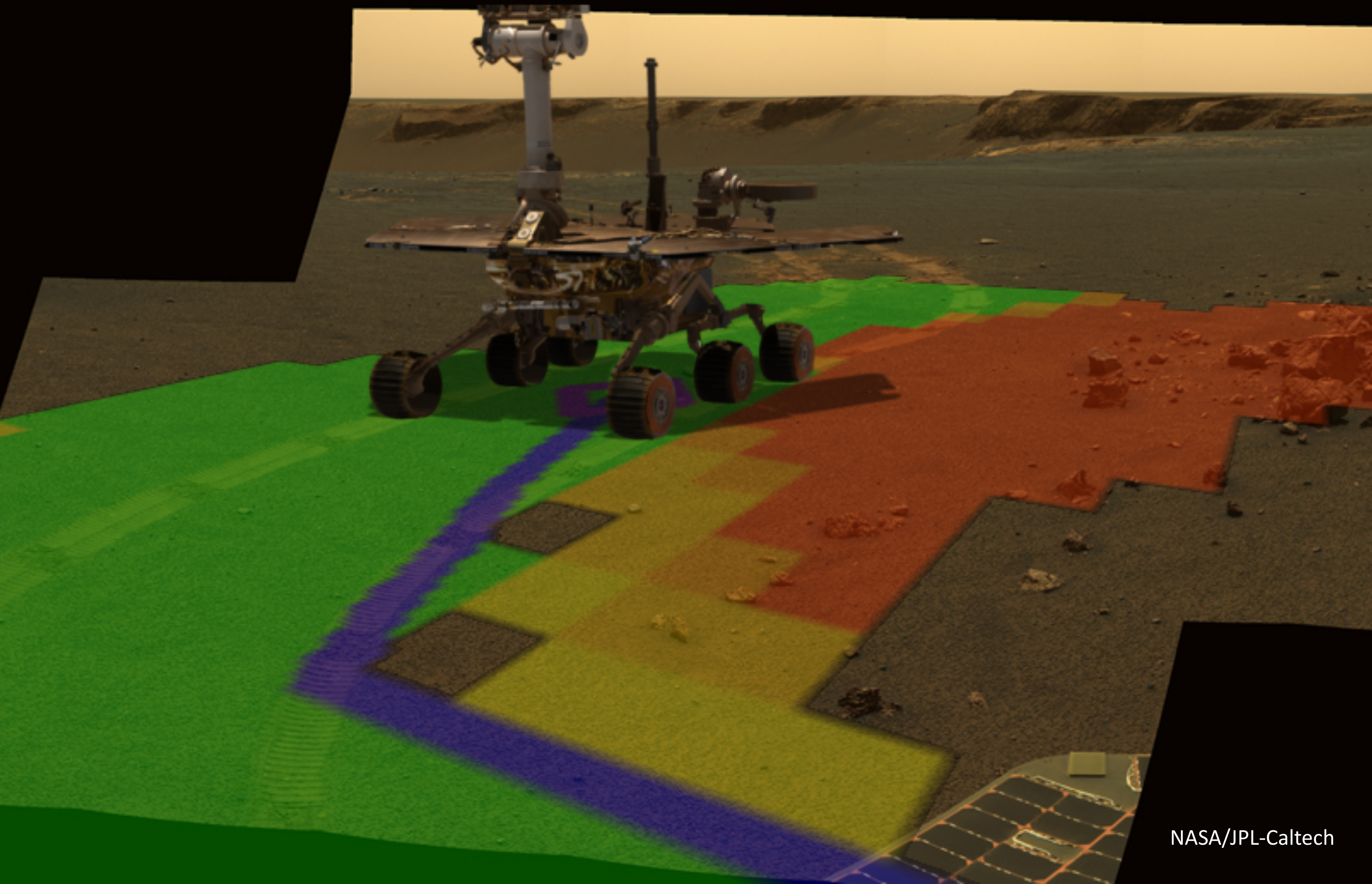
Overhead Imagery



Field D* Cost Map

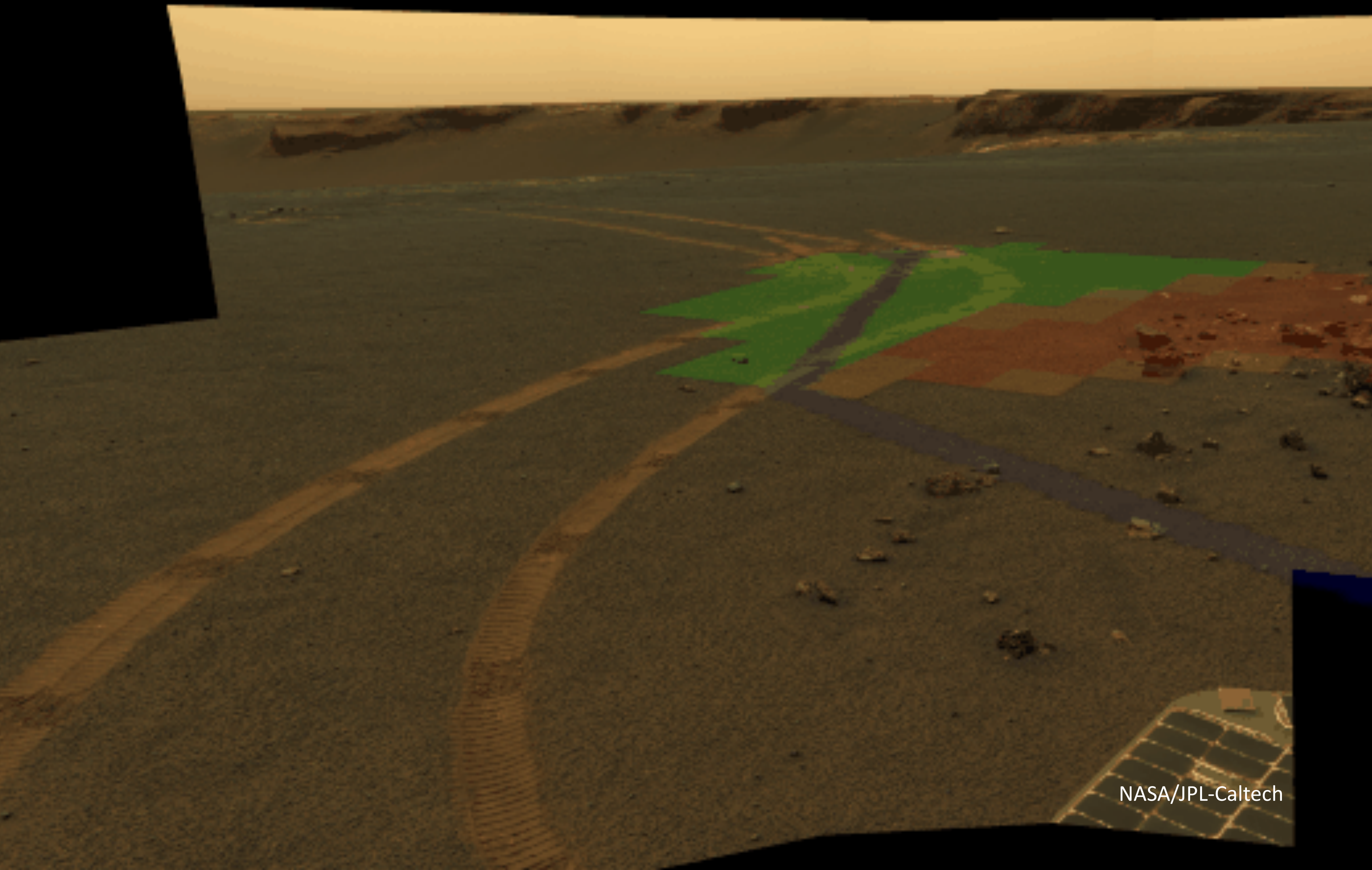
NASA/JPL-Caltech

D* Global Planner on Opportunity

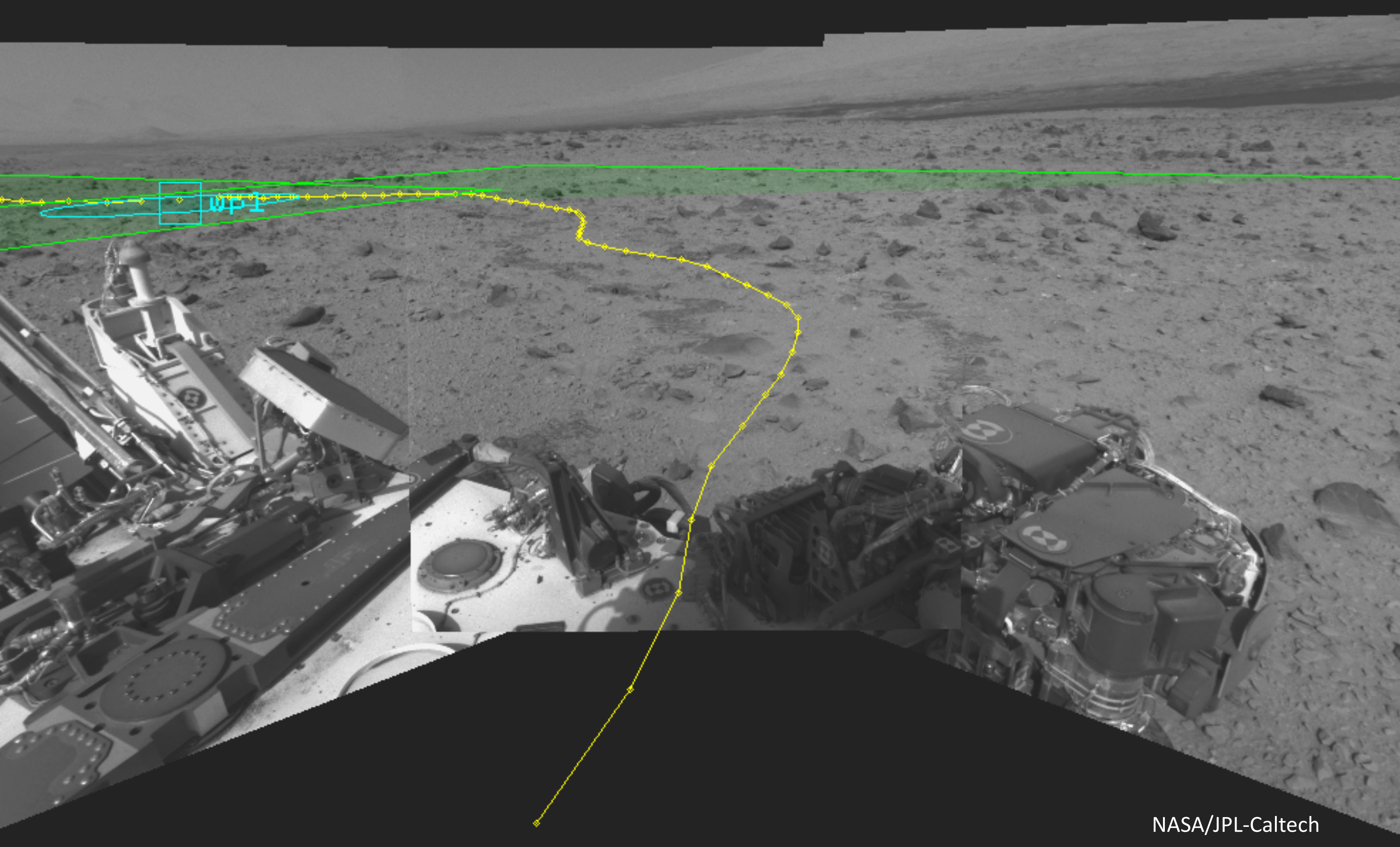


NASA/JPL-Caltech

D* Global Planner on Opportunity

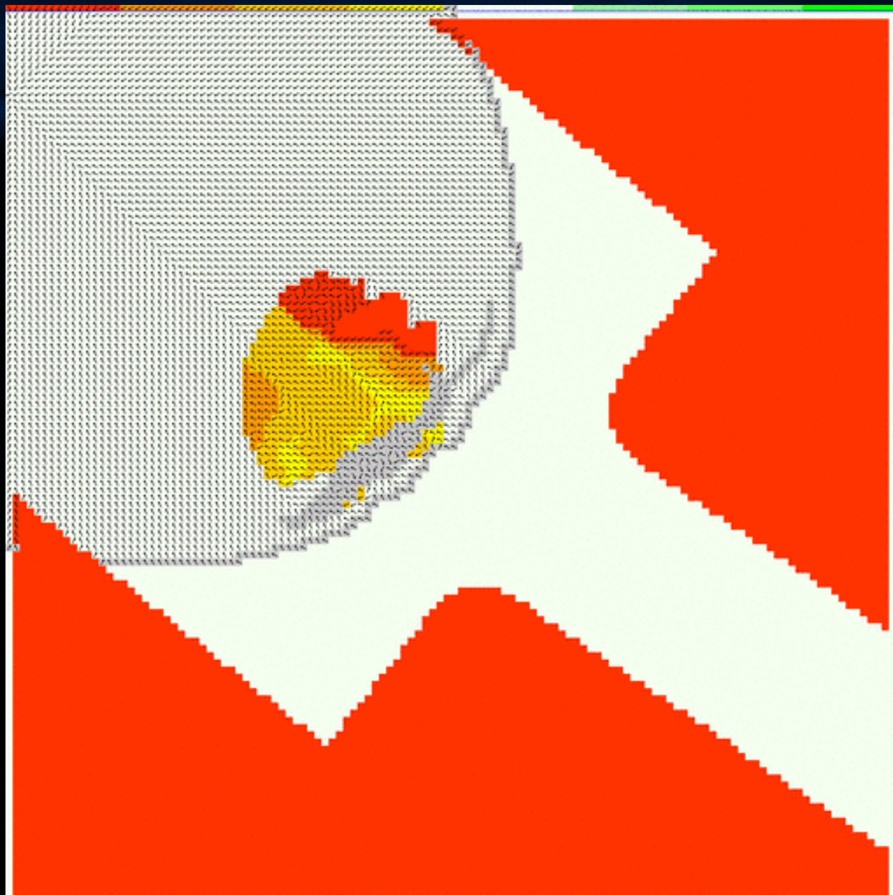


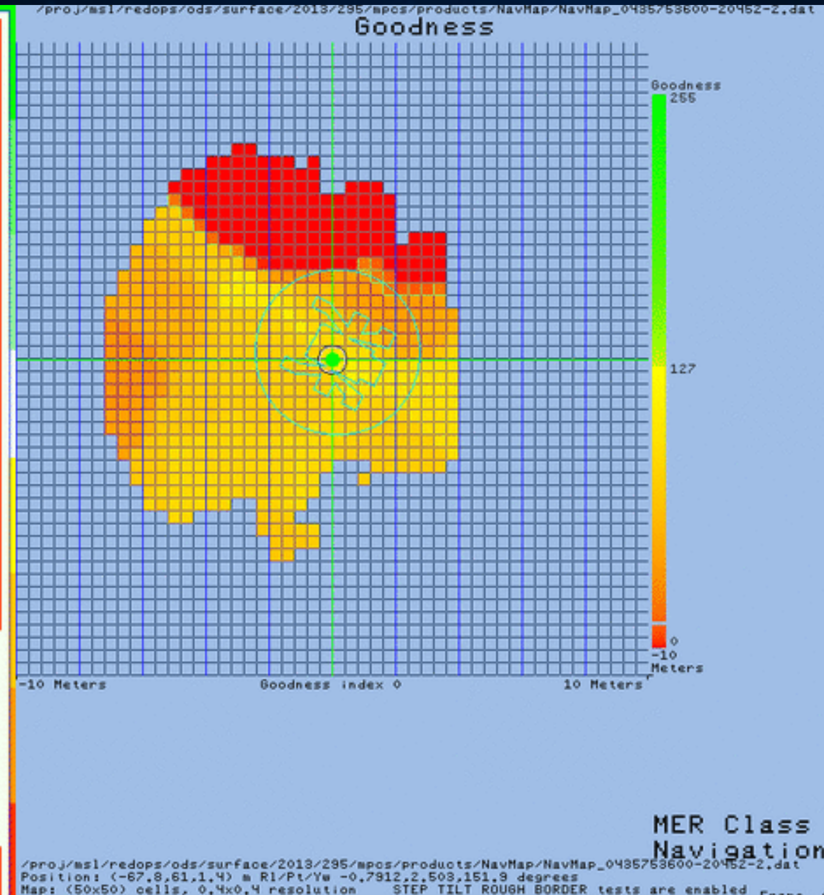
Curiosity Sol 431: Avoiding Rocks



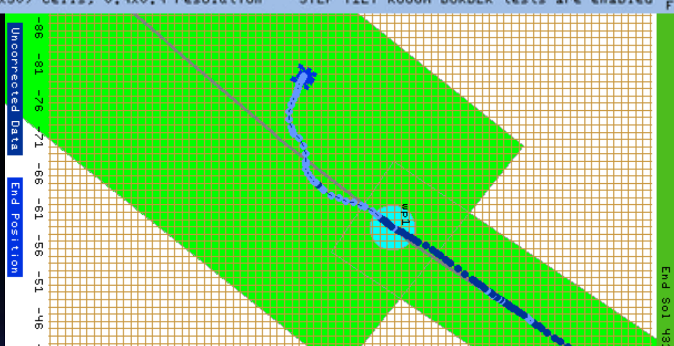
NASA/JPL-Caltech

Curiosity Sol 431: Avoiding Rocks

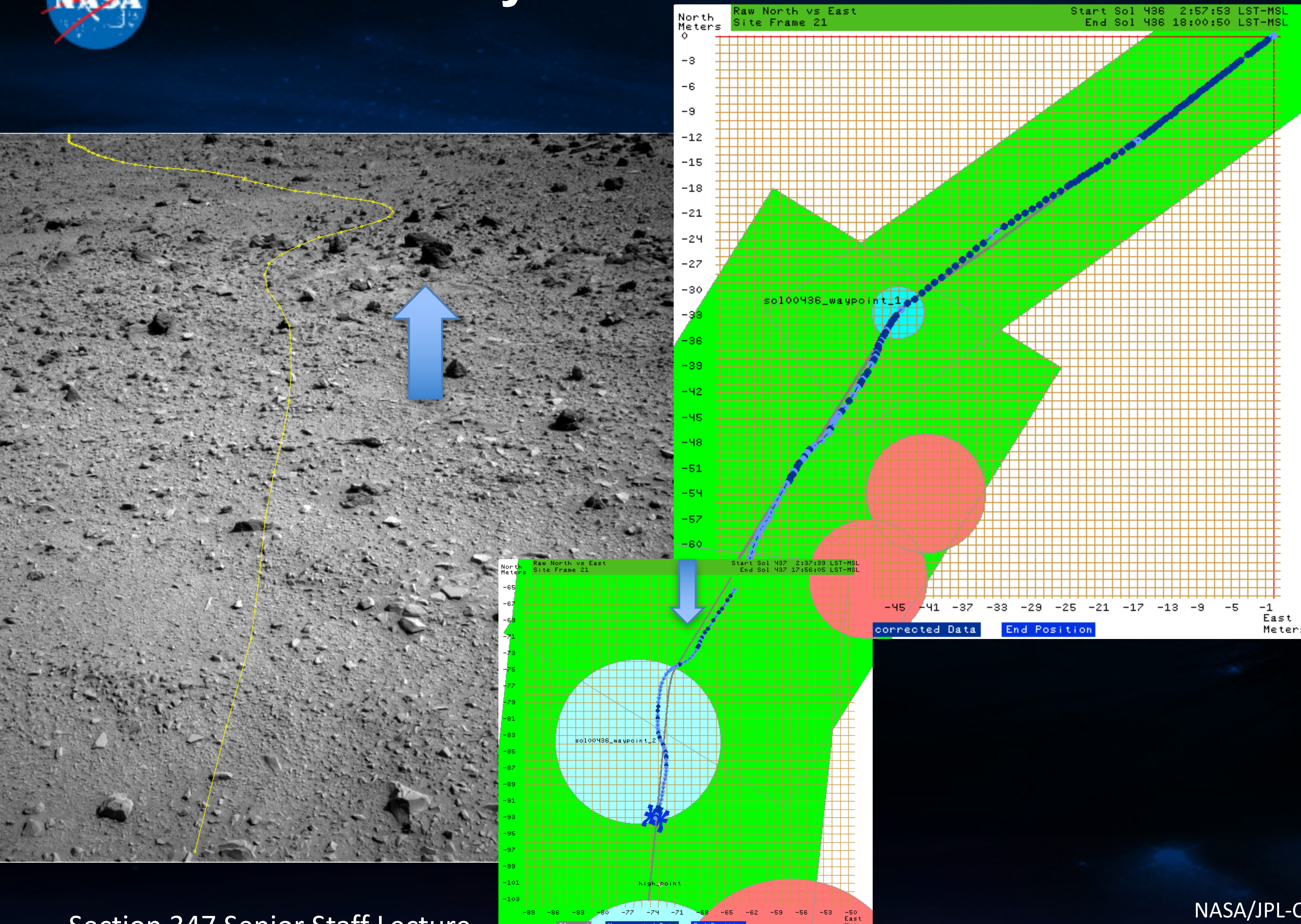




NASA/JPL-Caltech

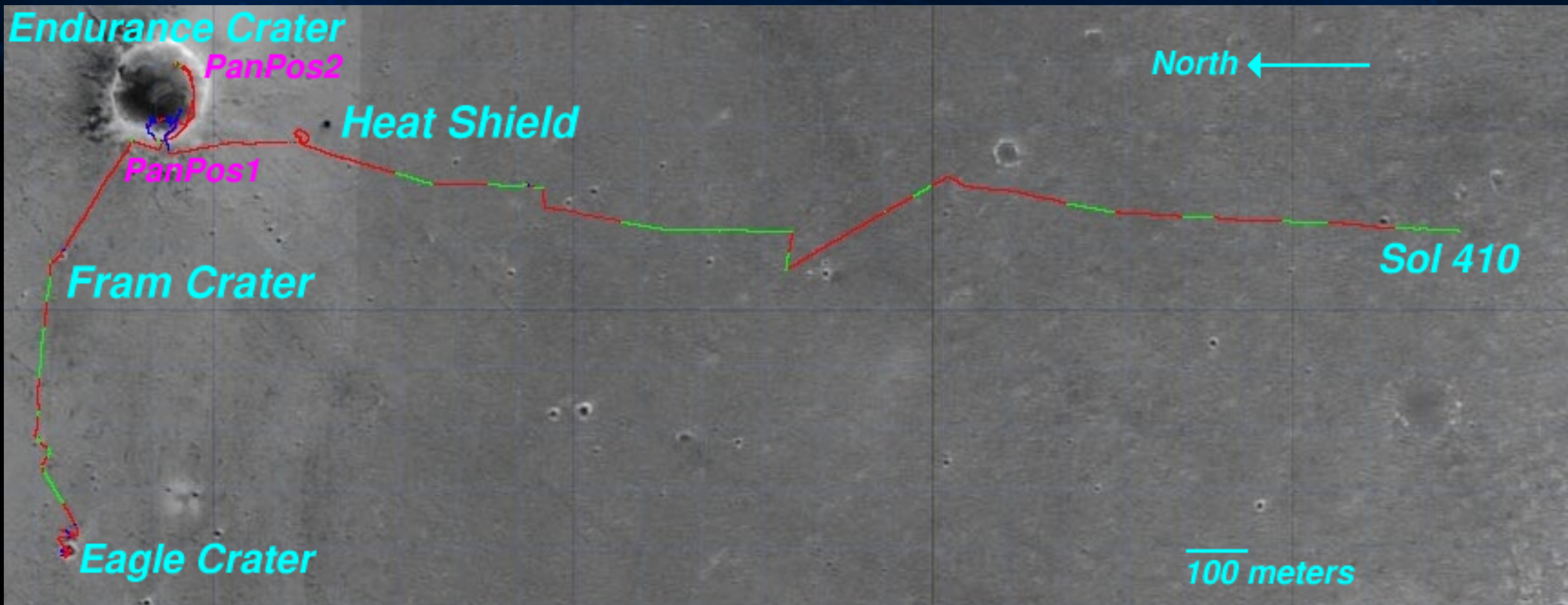


Curiosity Sol 436-437: Multi-sol Drive



NASA/JPL-Caltech

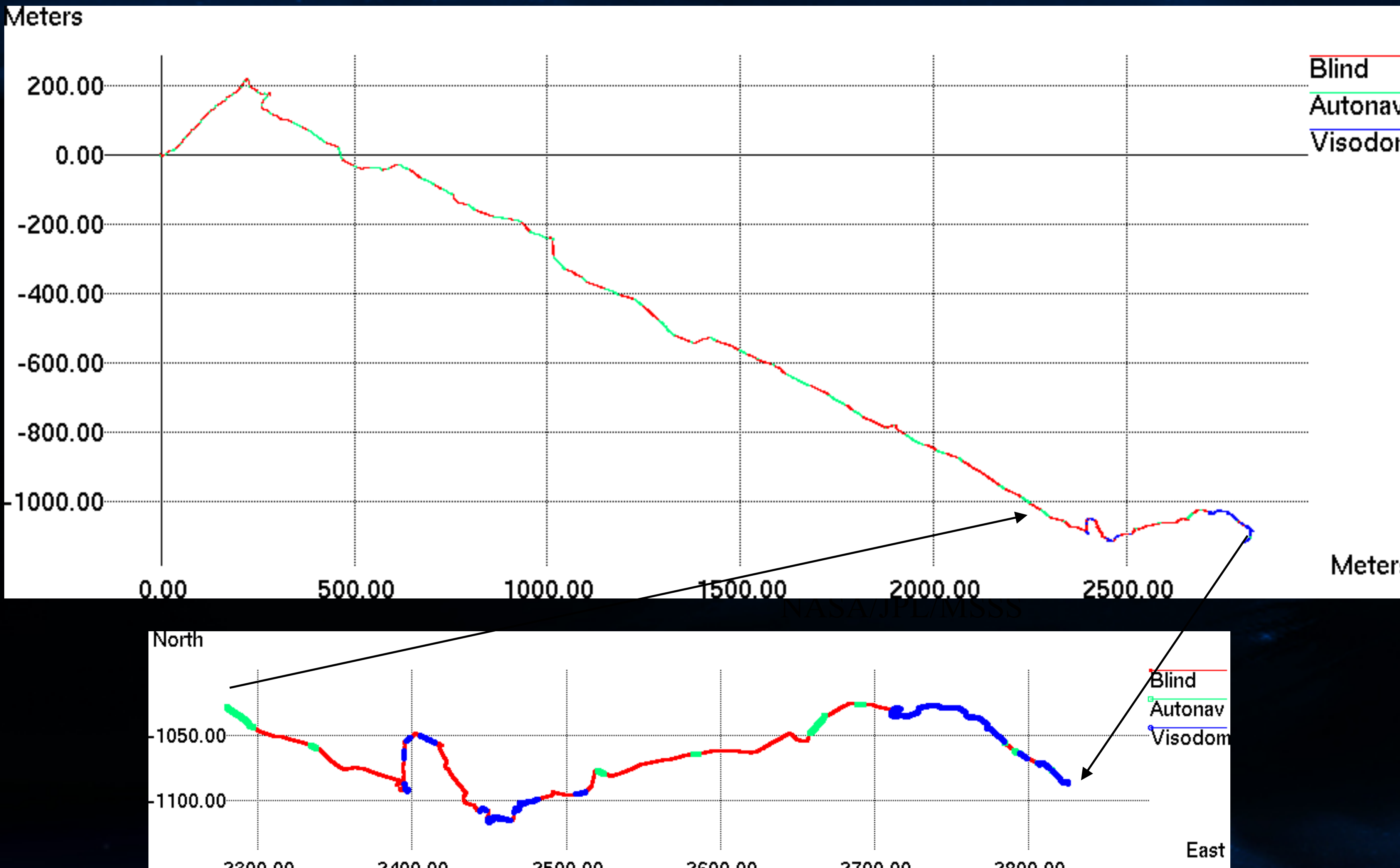
Opportunity Drives through Sol 410



NASA/JPL-Caltech

Driving Modes:
Blind
Autonav
Visodom

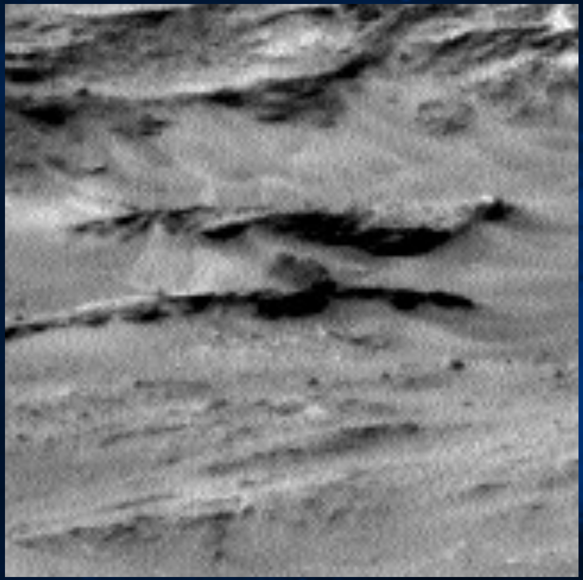
Spirit Drives through Sol 418



Visual Target Tracking

Sol 743

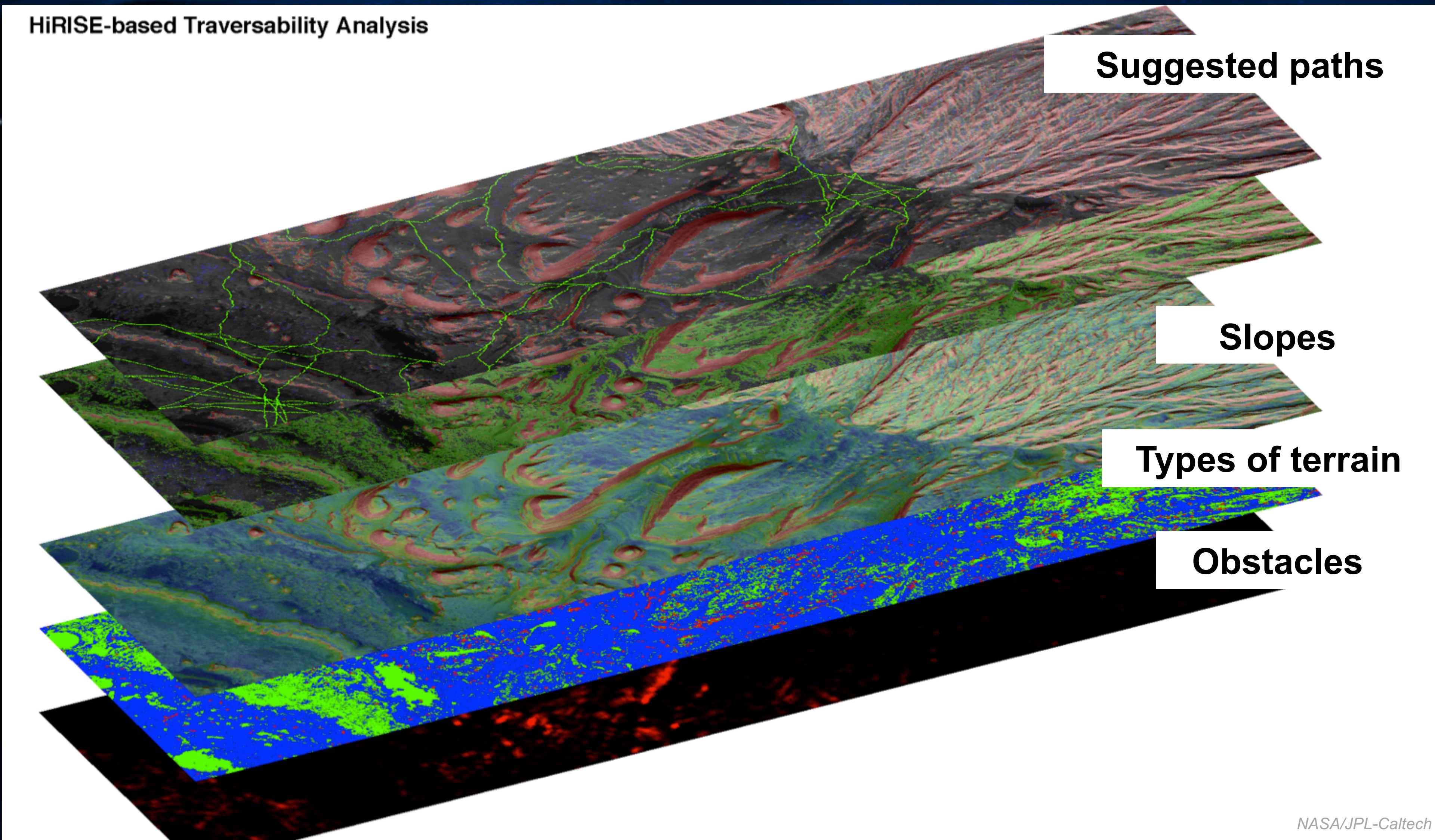
Sol 923



Sol 967

NASA/JPL-Caltech

Data from the Mars Reconnaissance Orbiter helps “see” several kilometers ahead, allowing for long term planning.



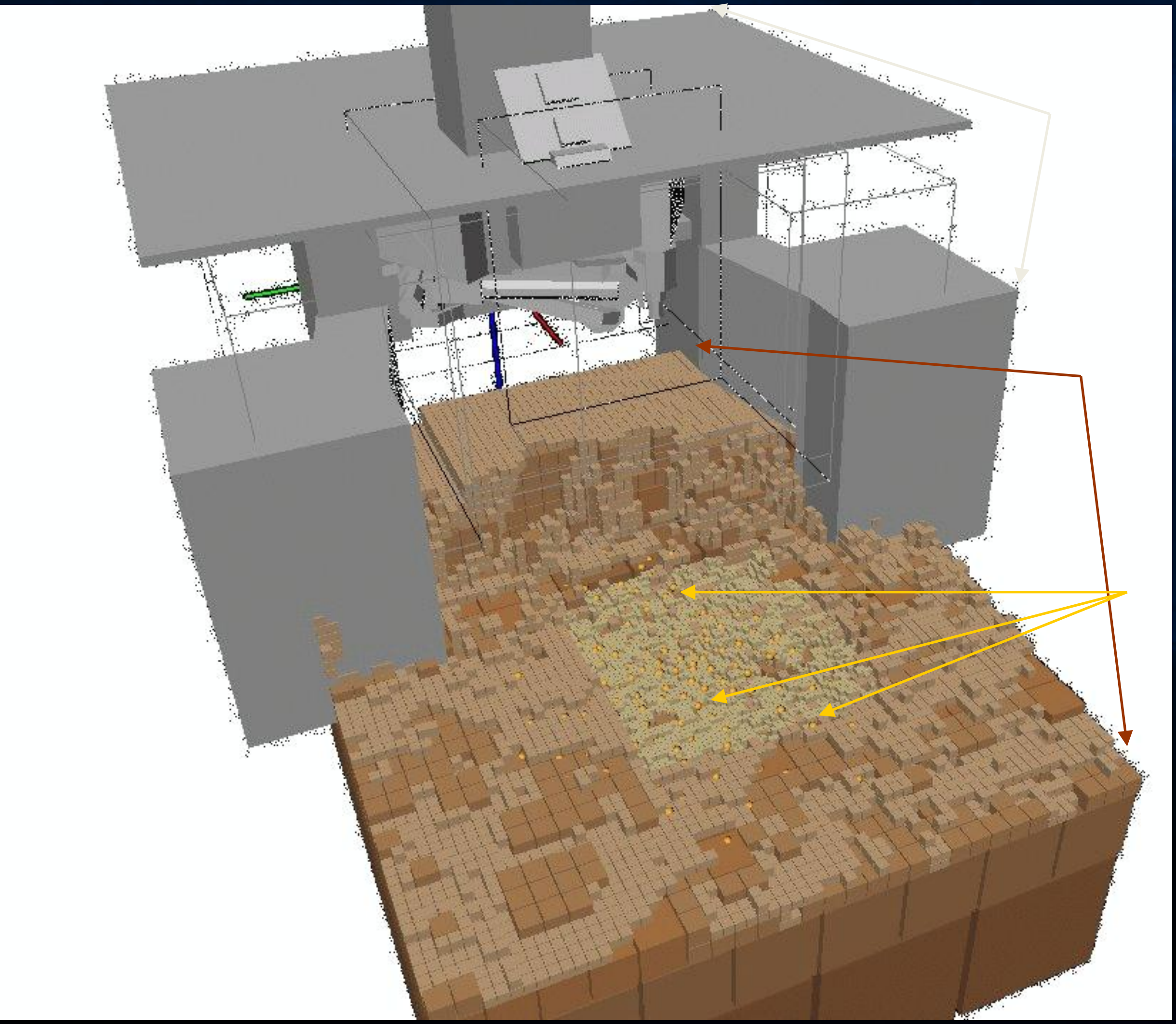
Autonomous Science: AEGIS

NASA/JPL-Caltech

Autonomous Science processing now performed onboard: automatic detection of Dust Devils and Clouds

Conserves downlink bandwidth, transmitting only those data known to be interesting

Autonomous Arm Placement: Spirit



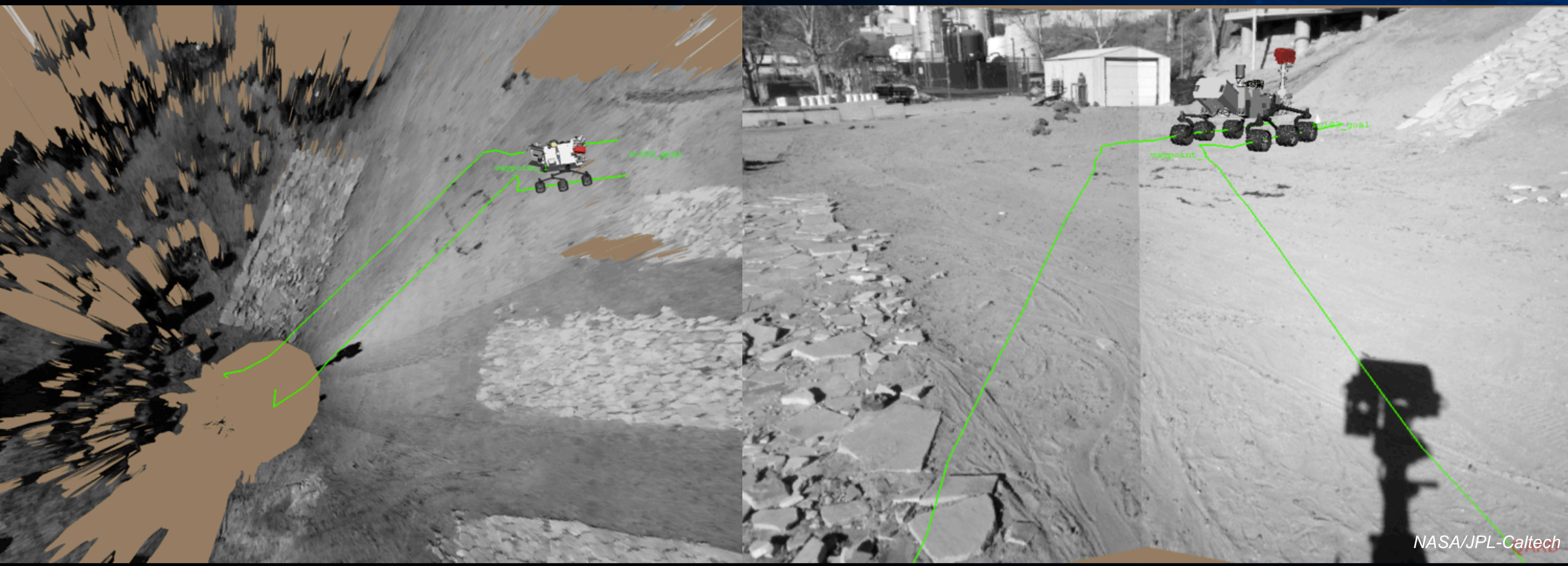
NASA/JPL-Caltech

Rover Exclusion Zones

High resolution terrain model processed onboard

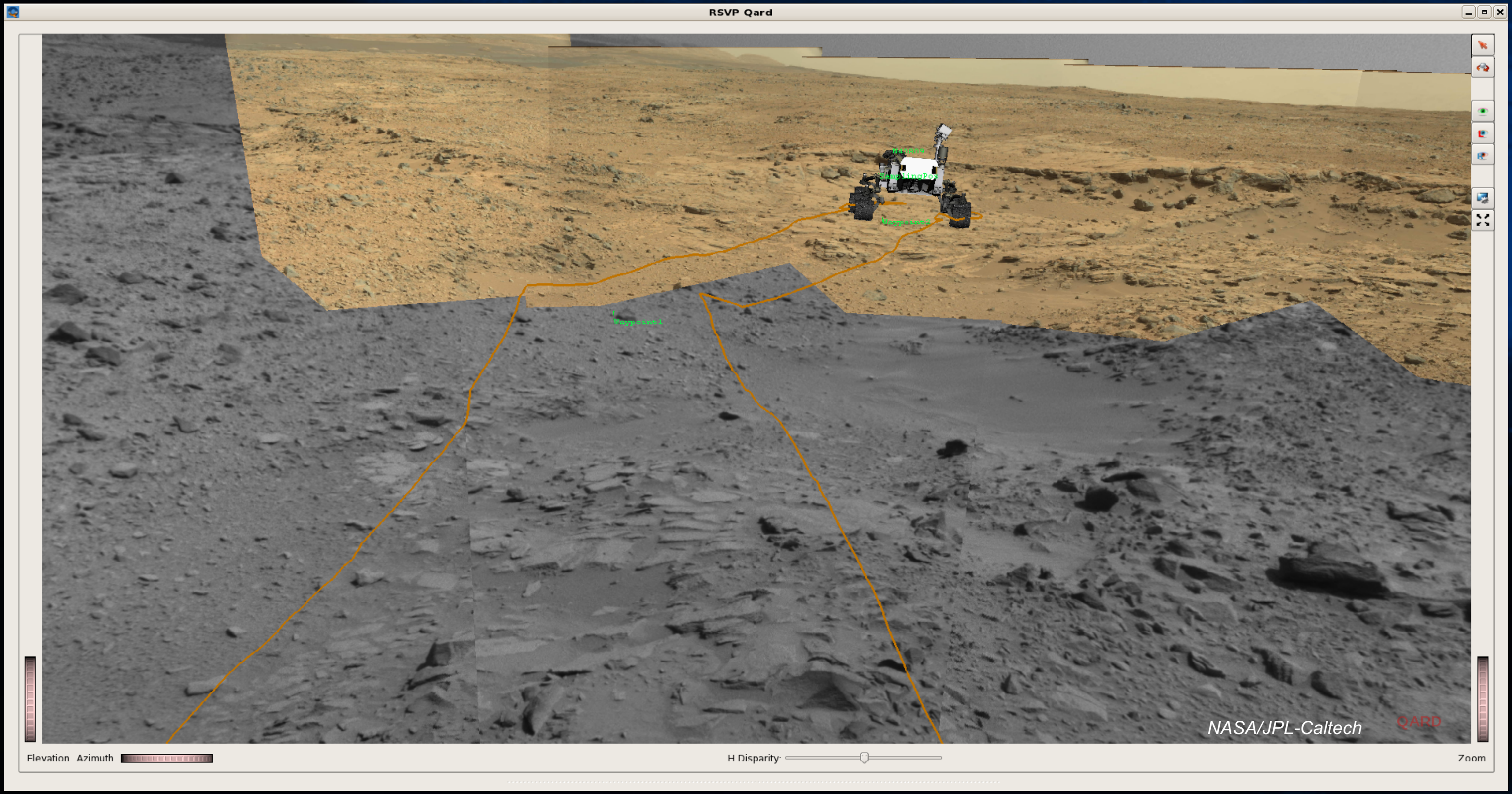
Potential IDD Placement targets

A previous day's images are fed into the Rover Simulation Visualization Program (RSVP) and 3D meshes are created.

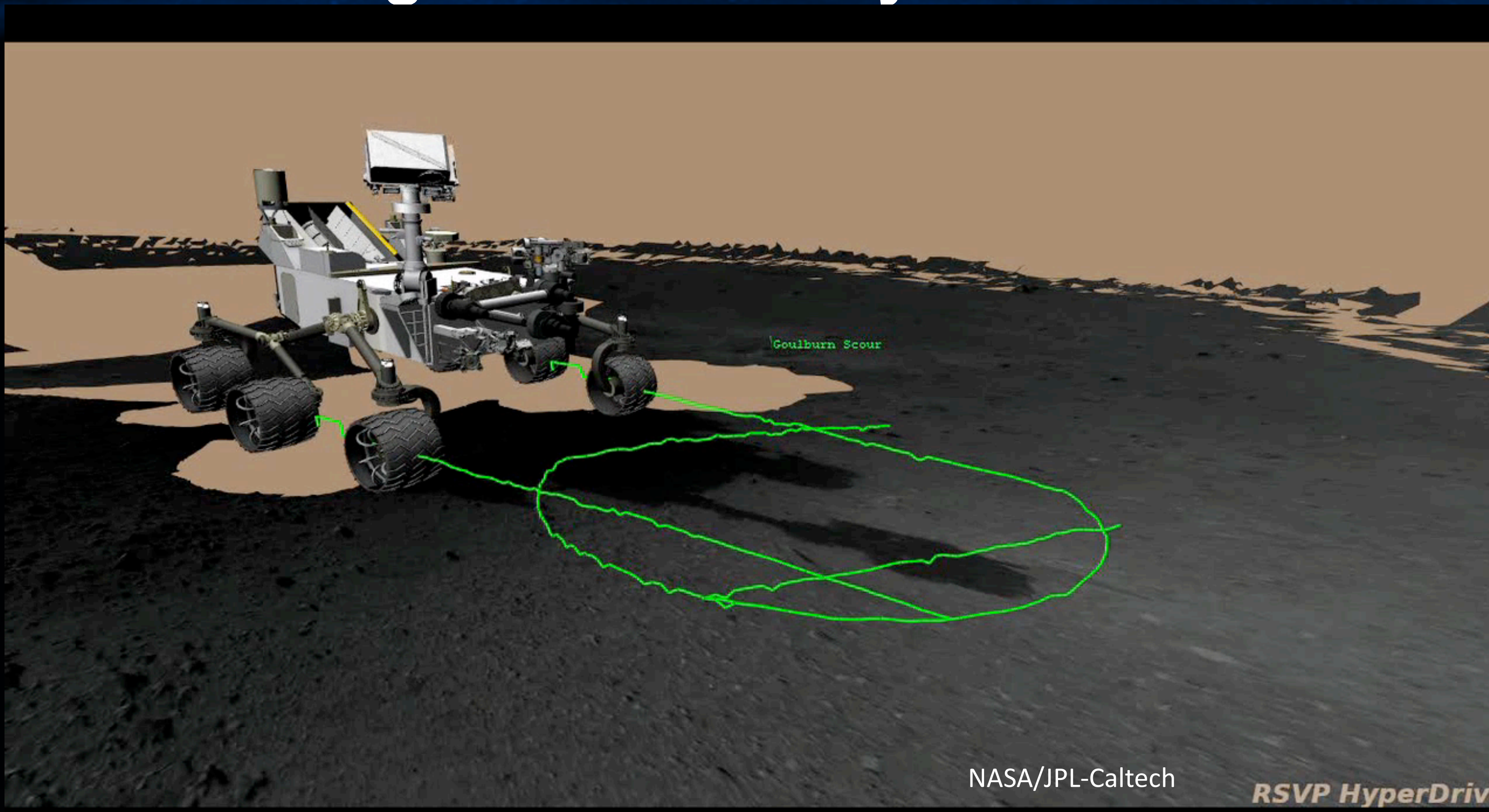


Rover drivers wear shuttered 3D goggles to view stereo imagery and 3D meshes

The Rover Simulation Visualization Program (RSVP) projects simulated drives into all available images.



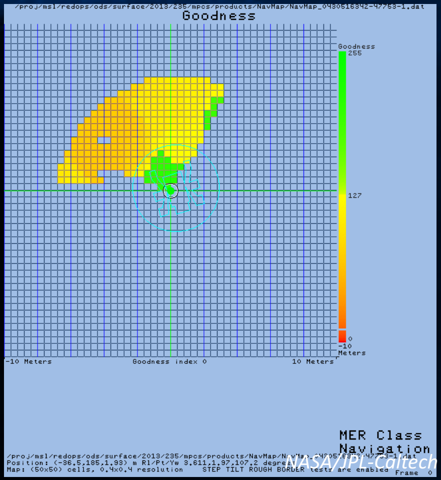
For "directed driving," drivers command the rover to move a certain distance over ground that they know is safe.



This is the fastest way to drive, because no predictive hazard processing is done, but distance is limited by what people can see. Curiosity will *always* stop the drive if a fault is detected!

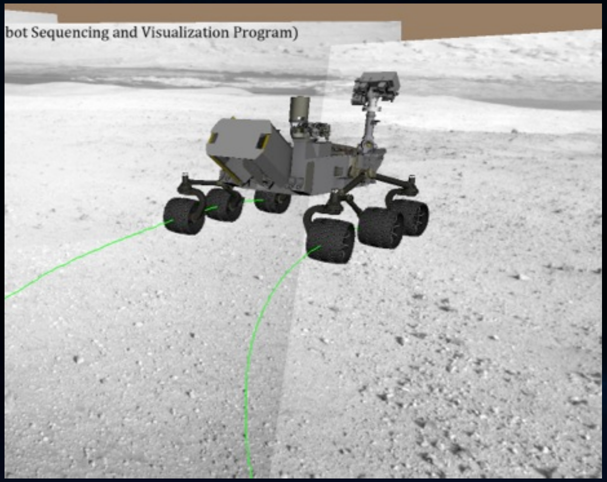
Curiosity Lets Human Drivers Choose the Level of Autonomy on Each Drive

Visual odometry, or Slip Check + “Auto”



Auto-navigation; Geometric Hazard Detection and Avoidance

Visual Target Tracking



Directed driving

NASA/JPL-Caltech

Unexpected Challenges!

Sol 122: VO vs IMU

- **By convention, any VO updates that measure more attitude change than the IMU does will be rejected; we tend to trust the IMU, especially over short distances**

- **On Sols 122-124, Curiosity drove using Visual Odometry (VO), but several VO updates were rejected!**

- **Turned out that VO was right! A parameter caused the IMU gyro-based attitude estimator to reject changes under high accelerations**

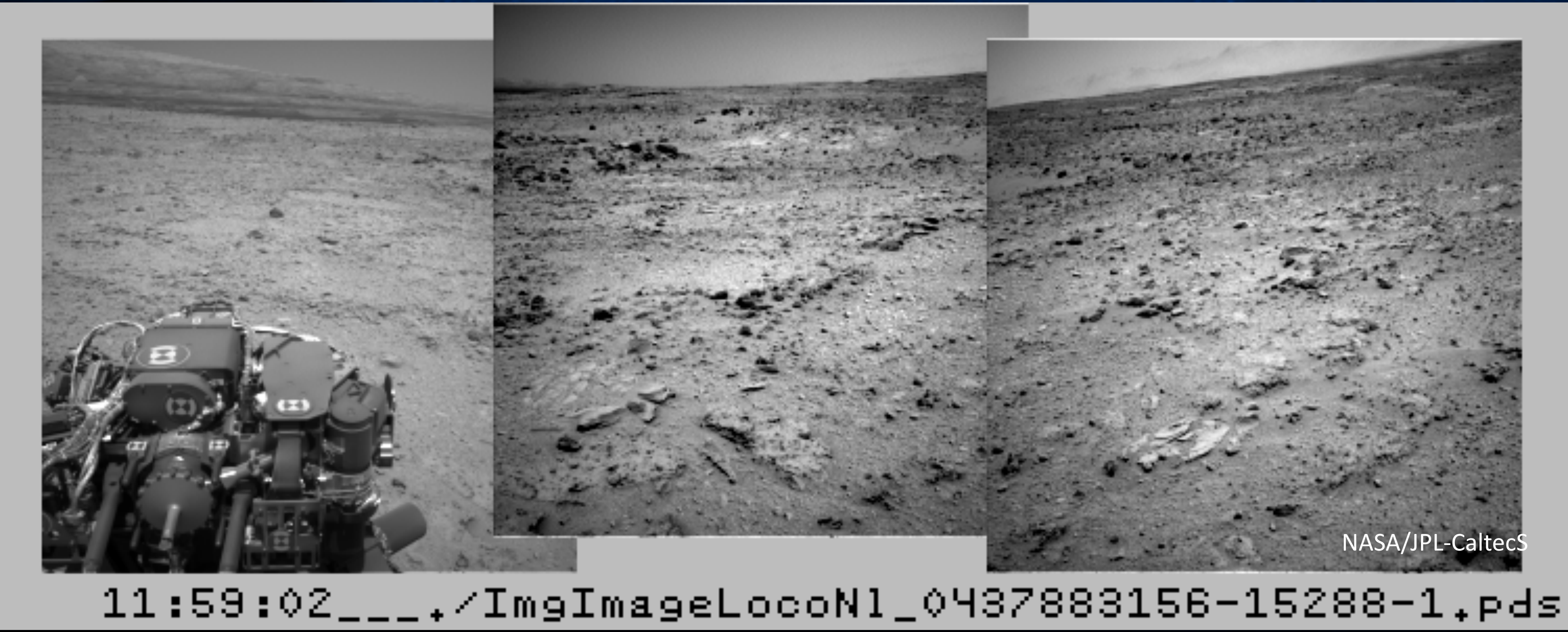
- **No more issues since updating that parameter**

- ***VO updates have failed to converge just 34 times out of 10,086 attempts as of sol 1294, and only 14 times for actual lack of texture; 99.86% success rate!***

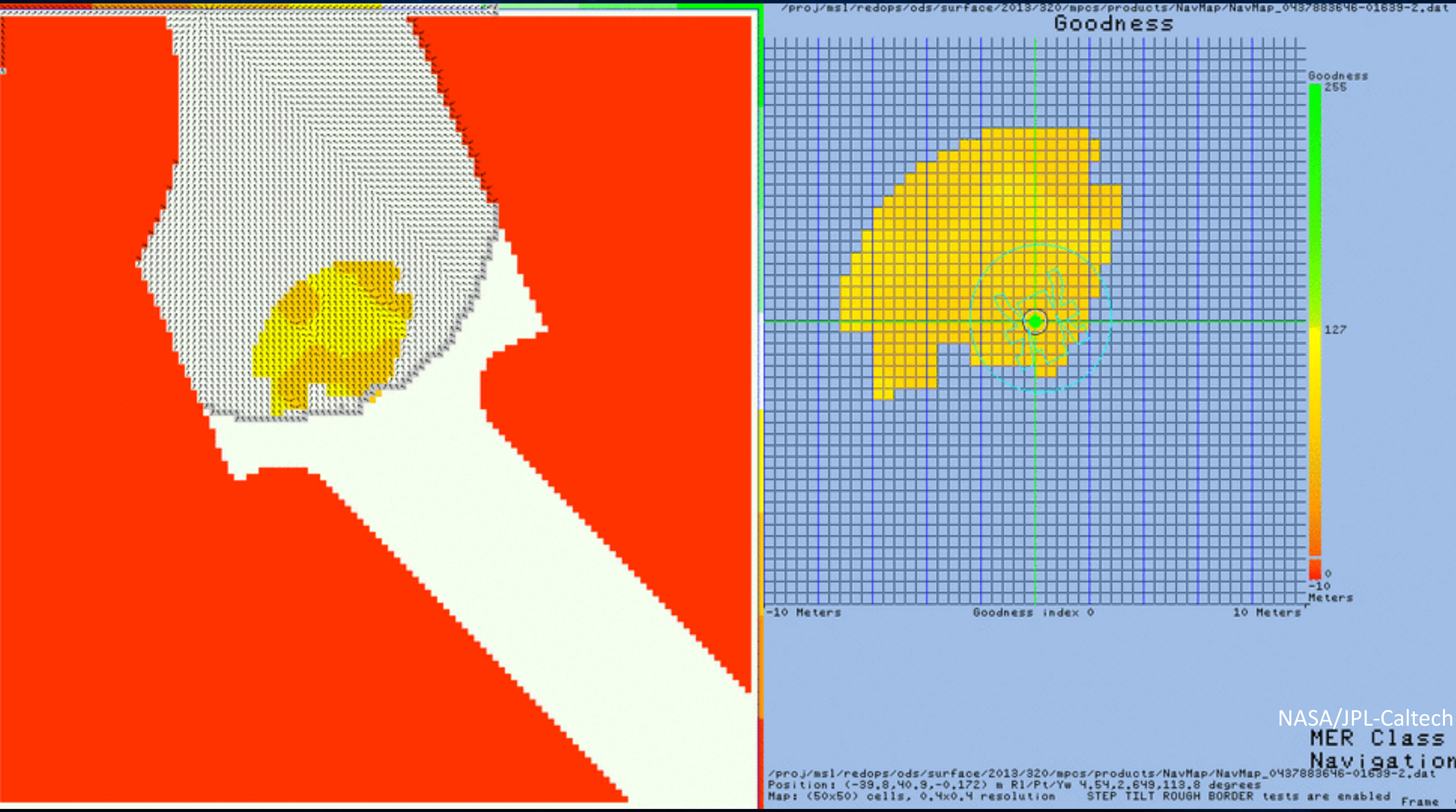
On sol 455, Curiosity Tried Multi-sol Driving again

- Multi-sol driving succeeded on sols 435-436!
- But the second try was halted by a drive stall, and interesting D* behavior on the first day, sol 455.

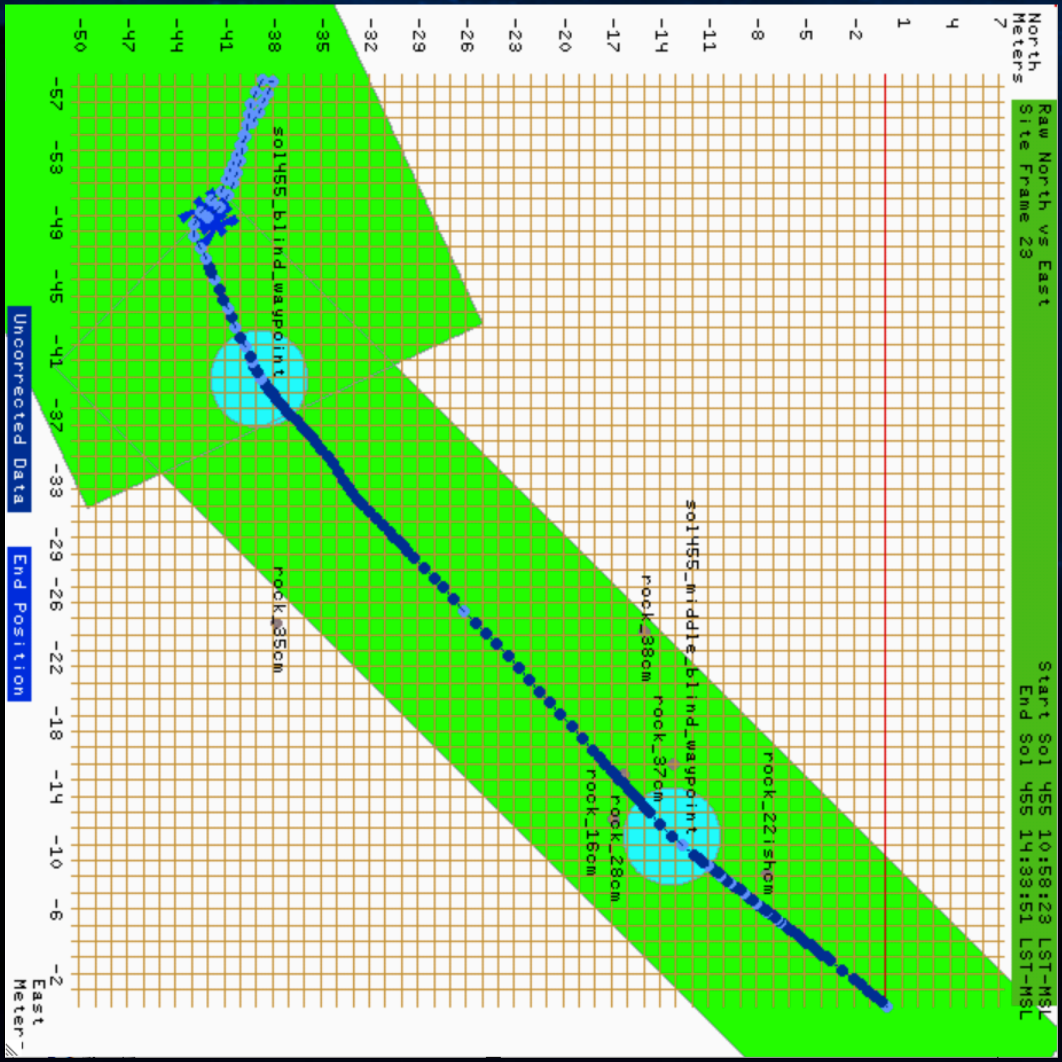
A Rover's-eye view of the Autonomous Portion of the sol 455 drive



Then, boxed in by Keepin Zones, D* tried backtracking!

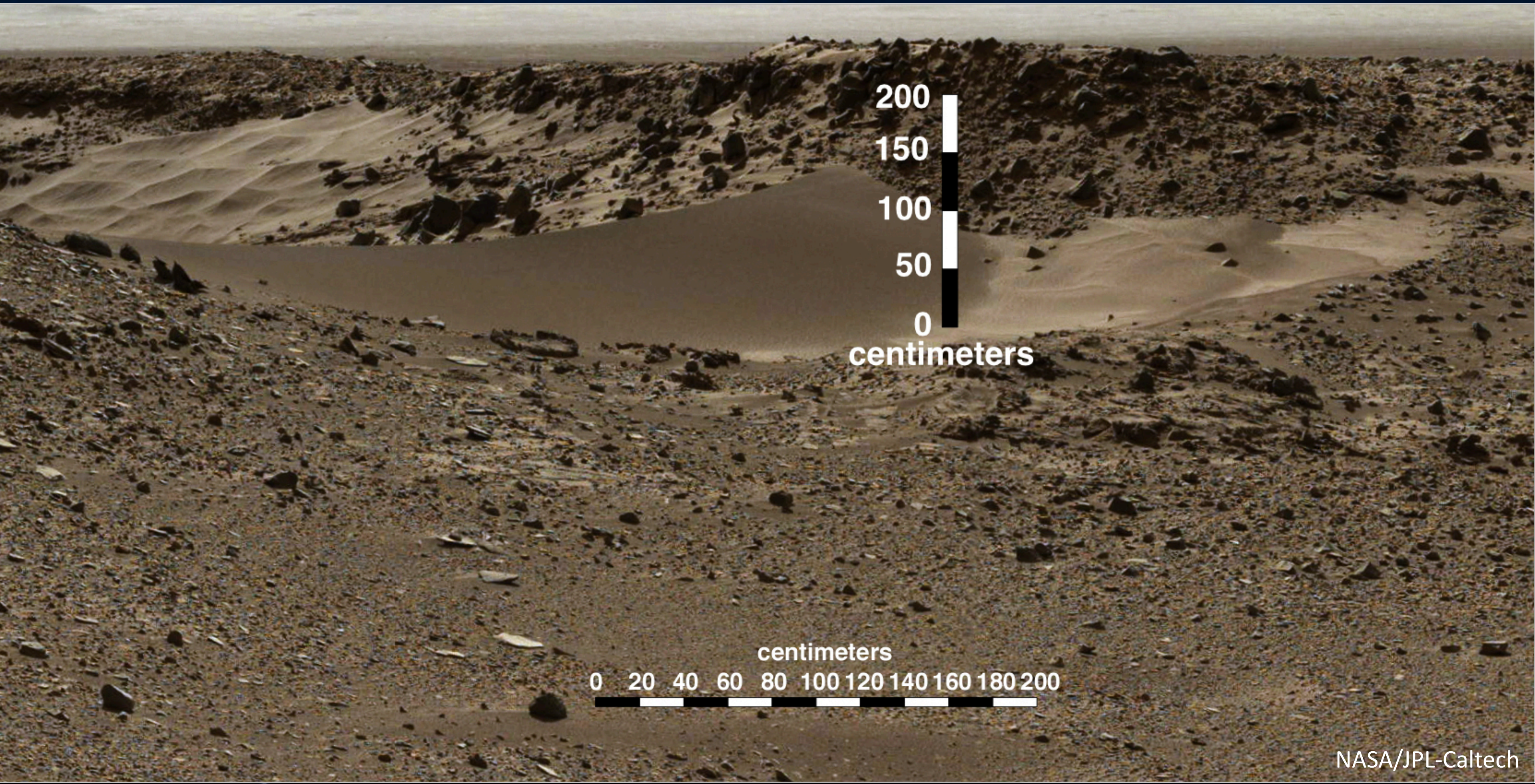


On sol 455, Curiosity encountered a small crater and began to drive around it



Small light blue dots represent the imaging steps

Sol 533-535: Dingo Gap

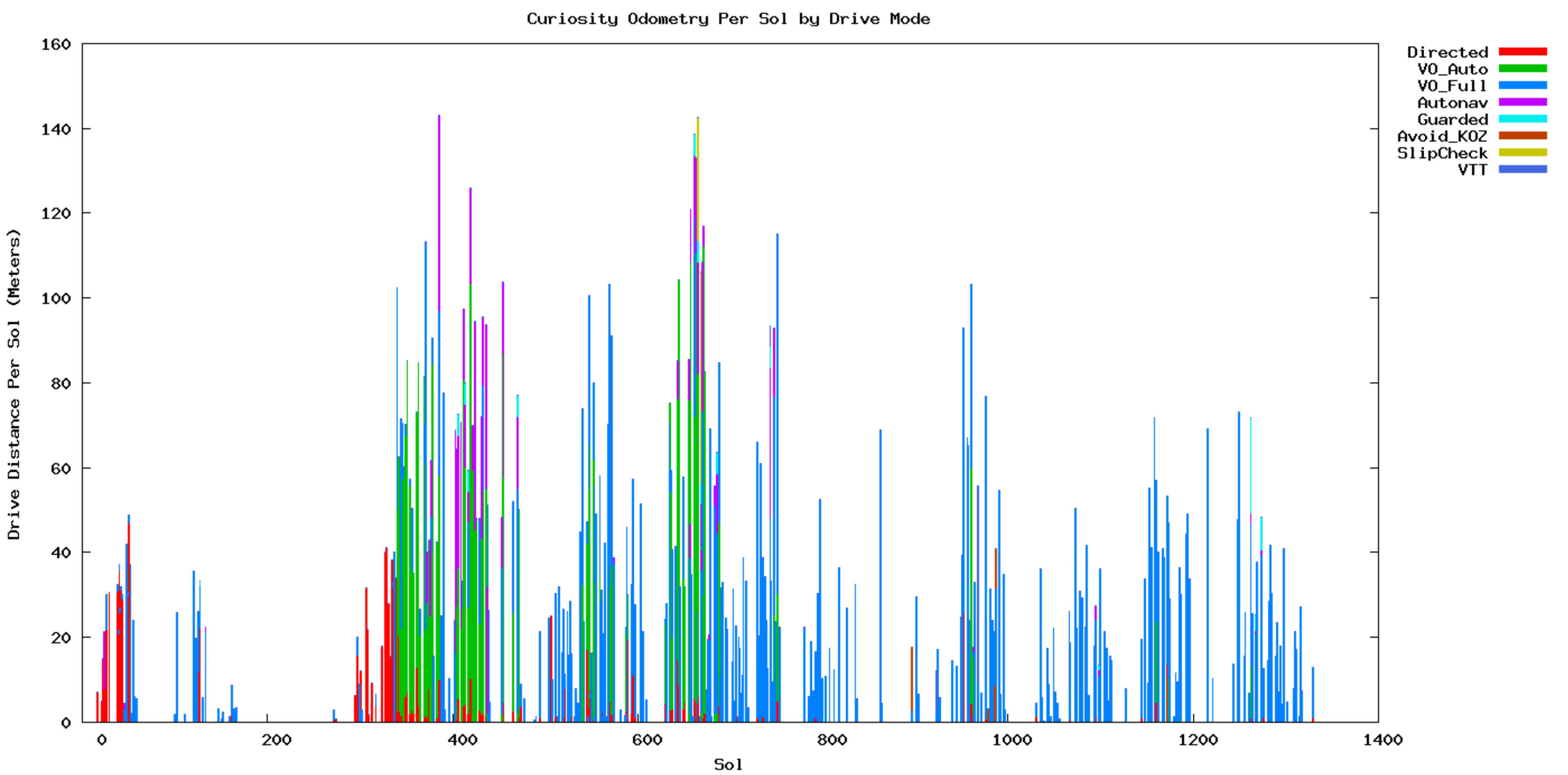


Sol 535: Climbing Over

NASA/JPL-Caltech

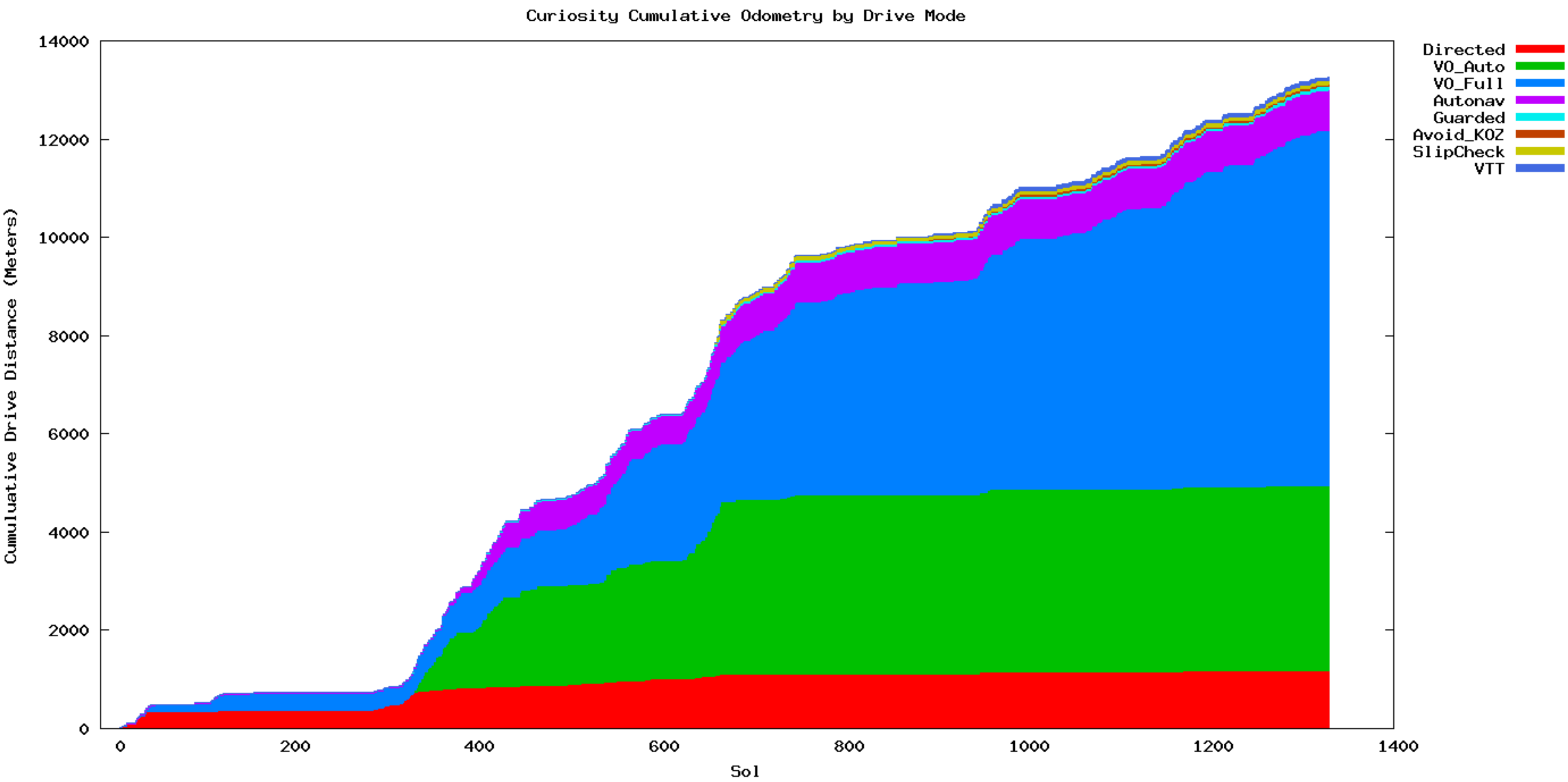
Statistics through sol 1330

Curiosity Odometry Per Sol



NASA/JPL-Caltech

Curiosity Cumulative Odometry



NASA/JPL-Caltech

Some Sojourner Onboard Capabilities

- Stereo Vision-based Obstacle Detection and Avoidance
  - 5 laser light stripes, processed at 4 locations for 20 samples
- Find Rock
- Thread the Needle Driving
- Fault Recovery

Some MER Onboard Capabilities

- Primary Mission
  - Local Path Selection
  - Dense Stereo Vision for …
  - … Terrain Assessment
  - AutoNav: Hazard Detection and Avoidance
  - Visual Odometry
- Extended Mission Proposal Included Research Infusion
  - Global Path Planner - Field D*
  - Visual Terrain Tracking
  - Autonomous Science, e.g. Dust Devil / Cloud Detection
  - Autonomous Instrument Placement

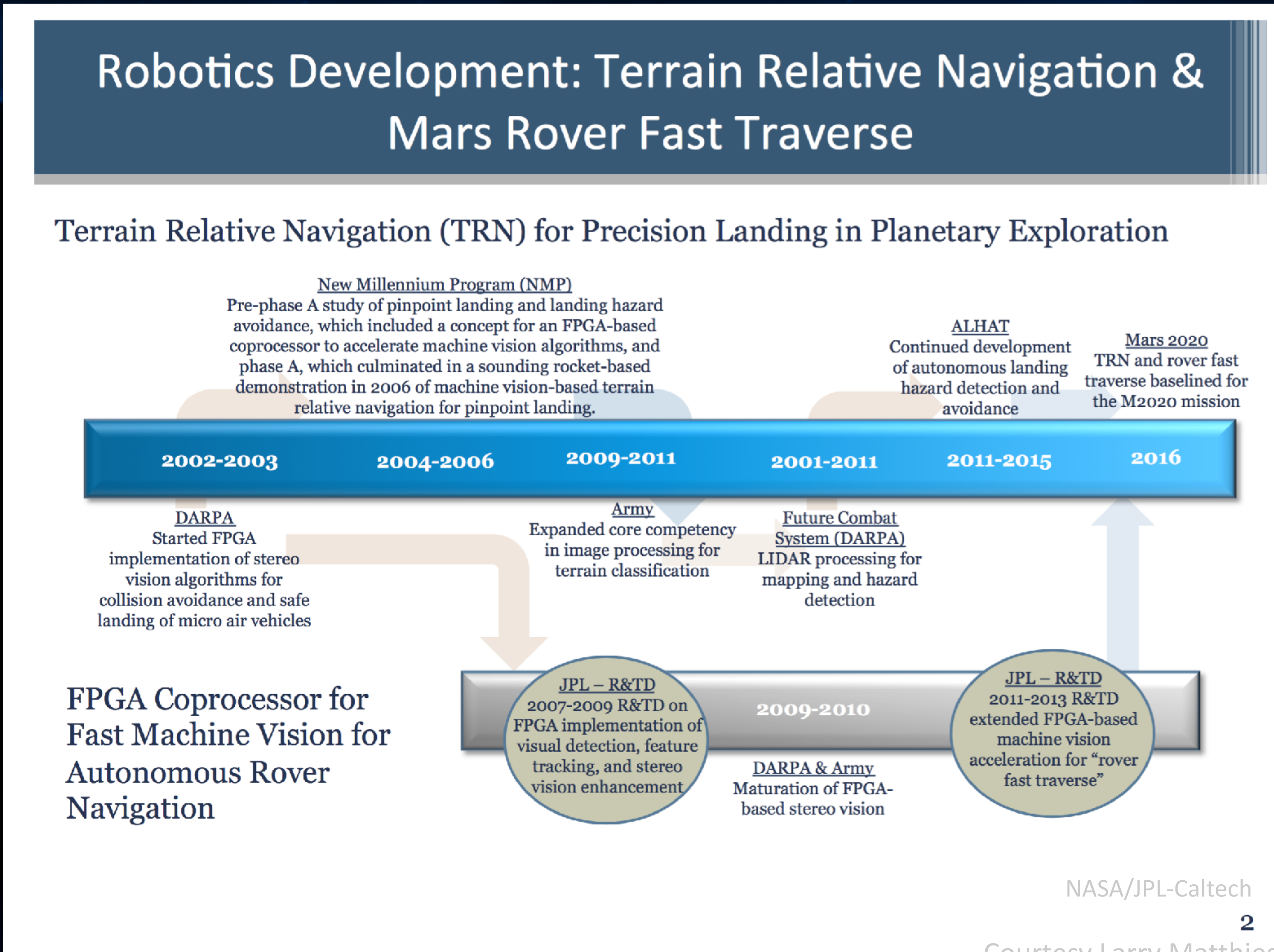
Some MSL Onboard Capabilities

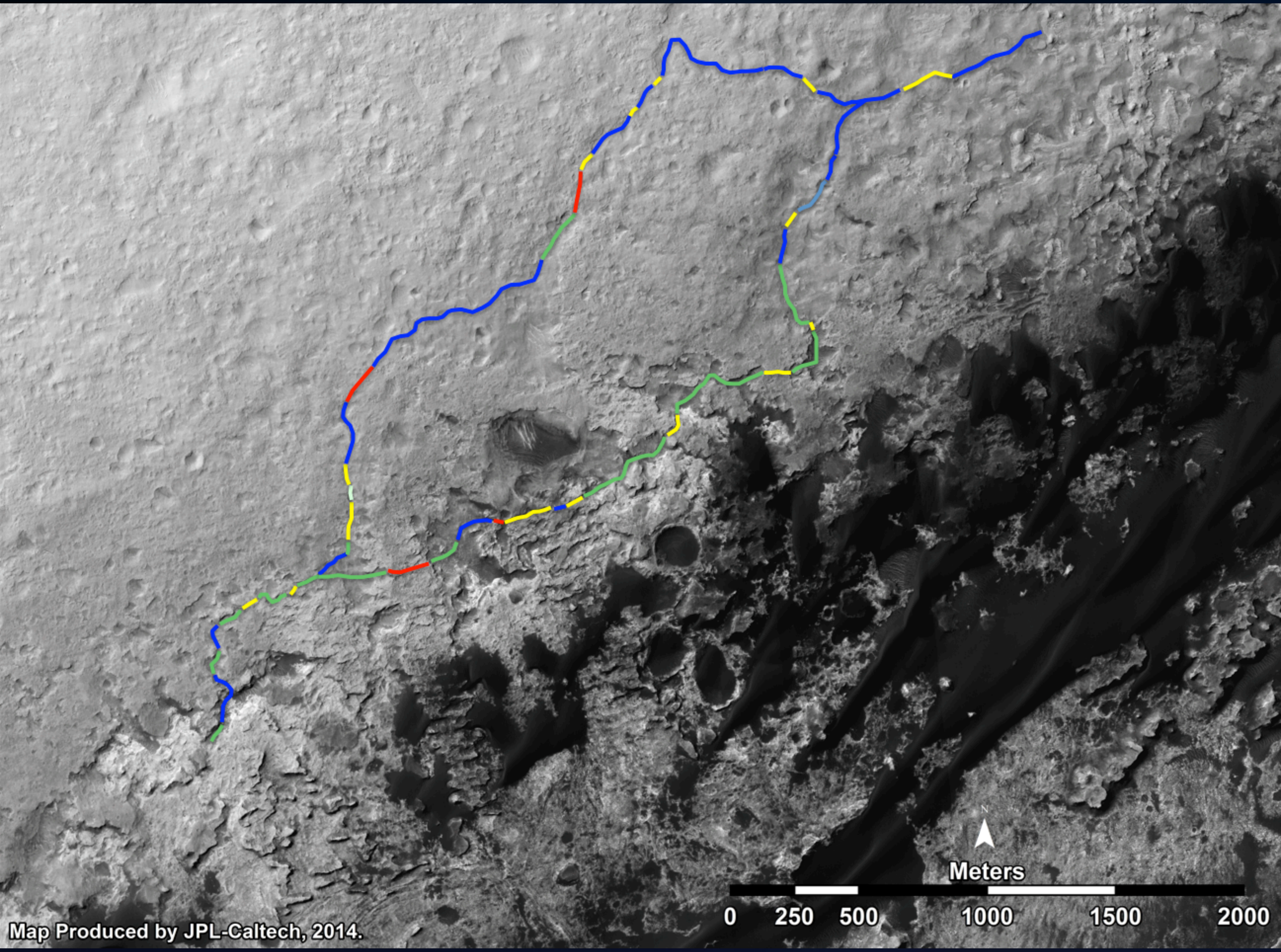
- Primary Mission
  - Local Path Selection and Global Path Planner - Field D*
  - Dense Stereo Vision for …
  - … Terrain Assessment
  - AutoNav: Hazard Detection and Avoidance
  - Visual Odometry
- Post-landing FSW updates
  - Visual Terrain Tracking
  - Autonomous Science – e.g., Dust Devil / Cloud Detection

What's Next is up to You!

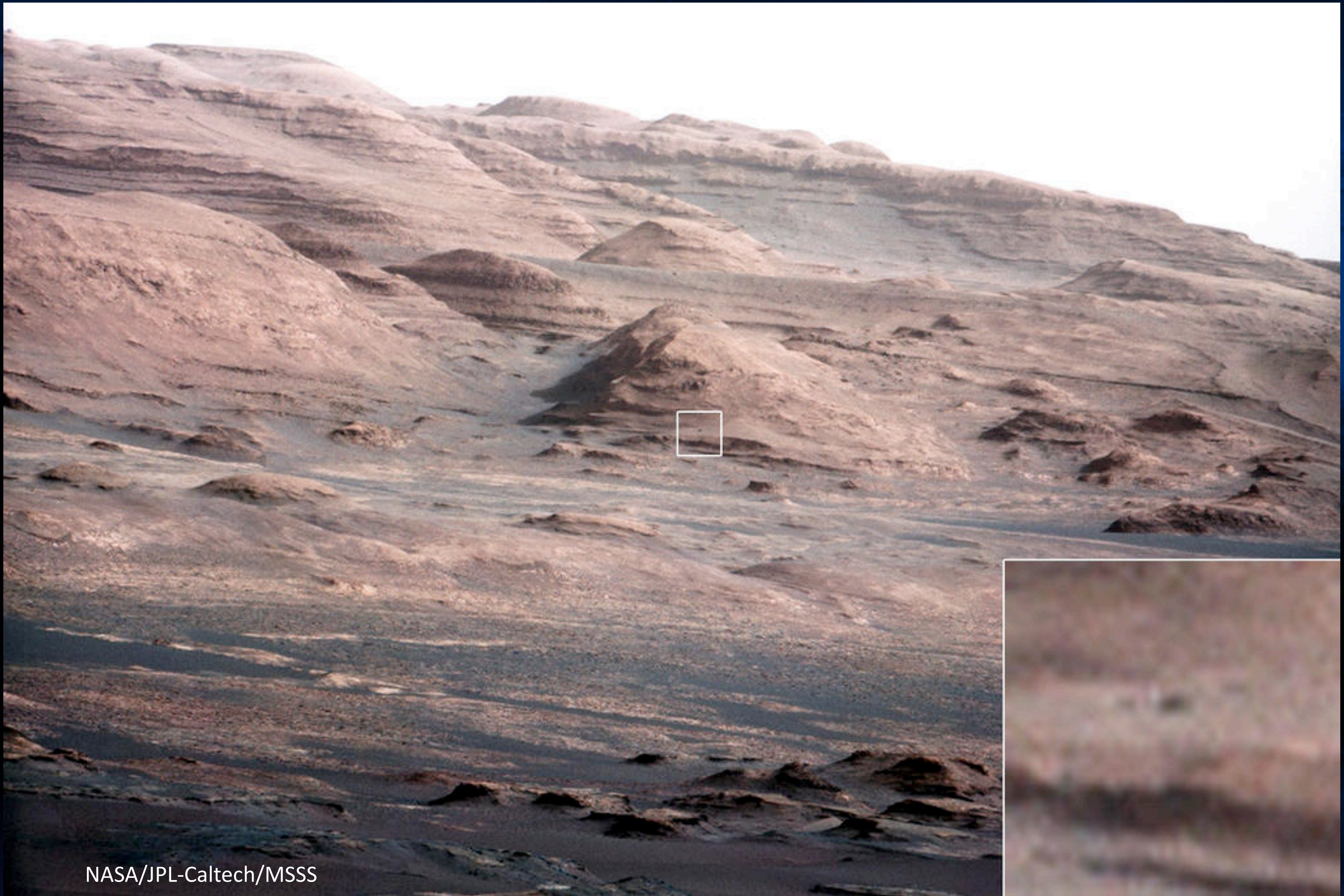
- Technology transfer into flight has several paths
- People: Join a flight project to support tech transfer
- Tech Push: MER 4th flight software release was coordinated as a tech transfer push by Project and Line Management
- Tech Pull: Anomalies are opportunities!

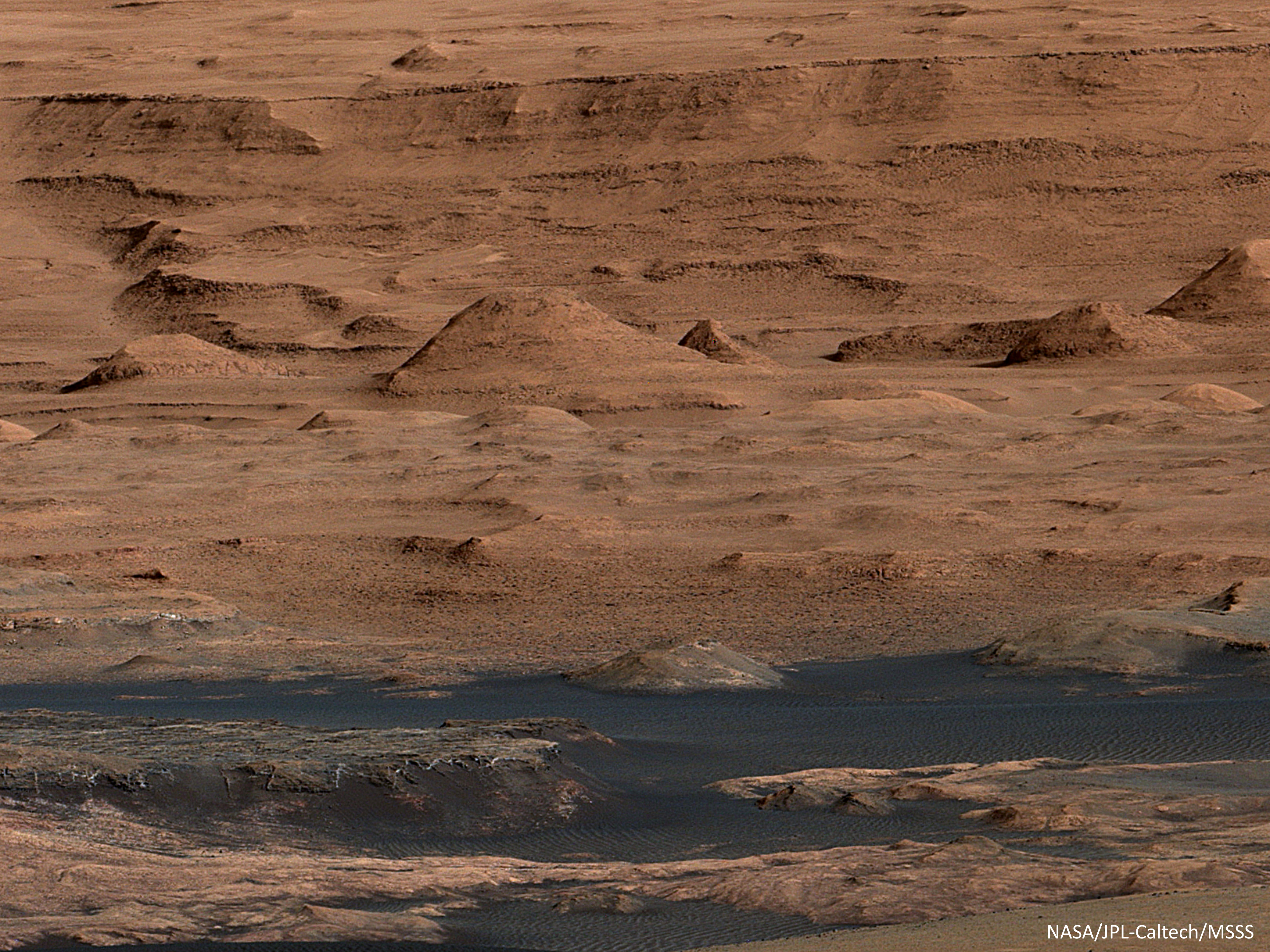
Navigation FGPA Coprocessors



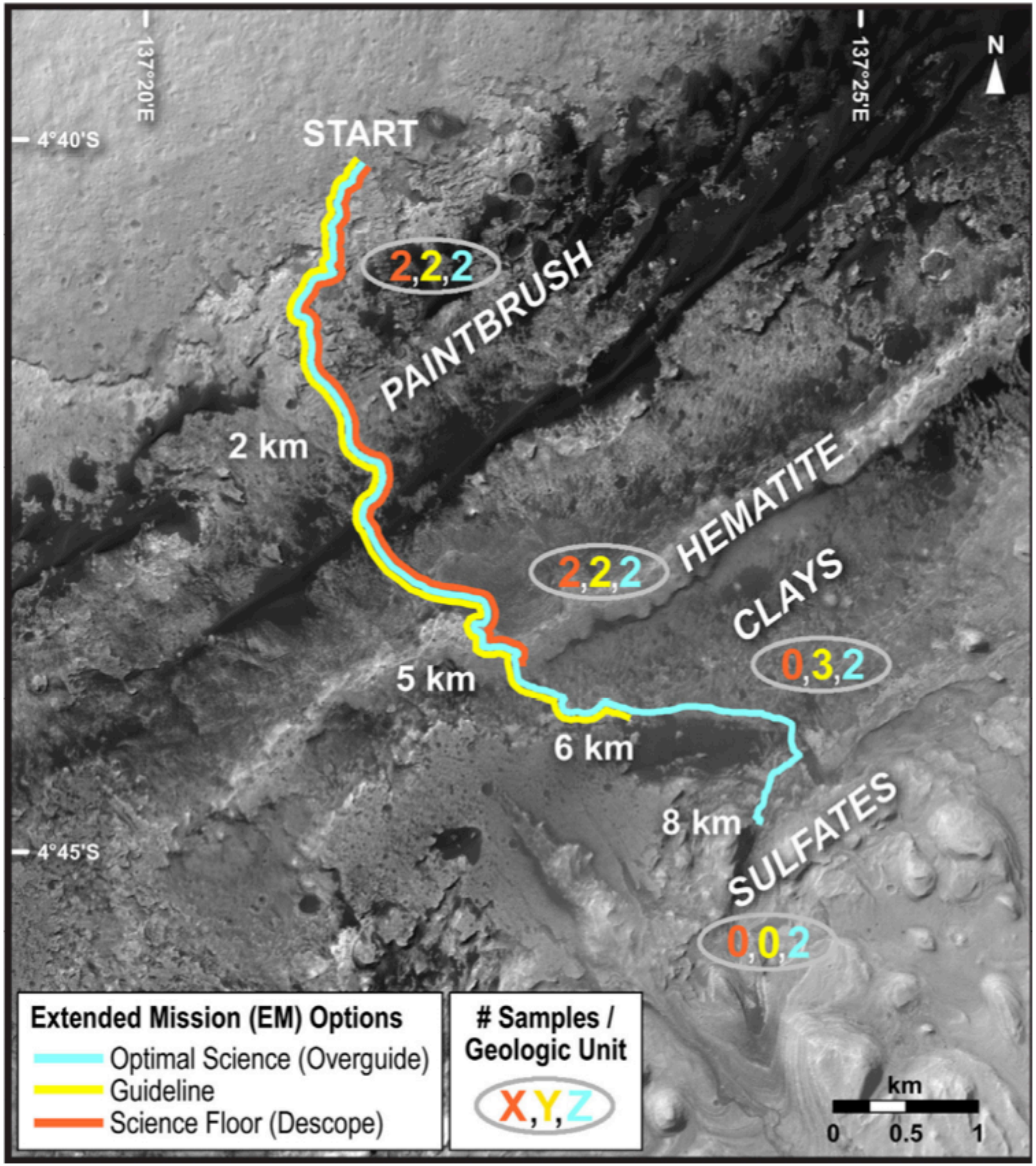

N
Meters
0 250 500 1000 1500 2000
Map Produced by JPL-Caltech, 2014.

The Road Ahead




NASA/JPL-Caltech/MSSS

Targets for Exploration



137°20'E
137°25'E
N
4°40'S
4°45'S
START
2,2,2
PAINTBRUSH
2 km
HEMATITE
2,2,2
CLAYS
0,3,2
5 km
6 km
8 km
SULFATES
0,0,2
Extended Mission (EM) Options
Optimal Science (Overguide)
Guideline
Science Floor (Descope)
Samples / Geologic Unit
X,Y,Z
km
0
0.5
1