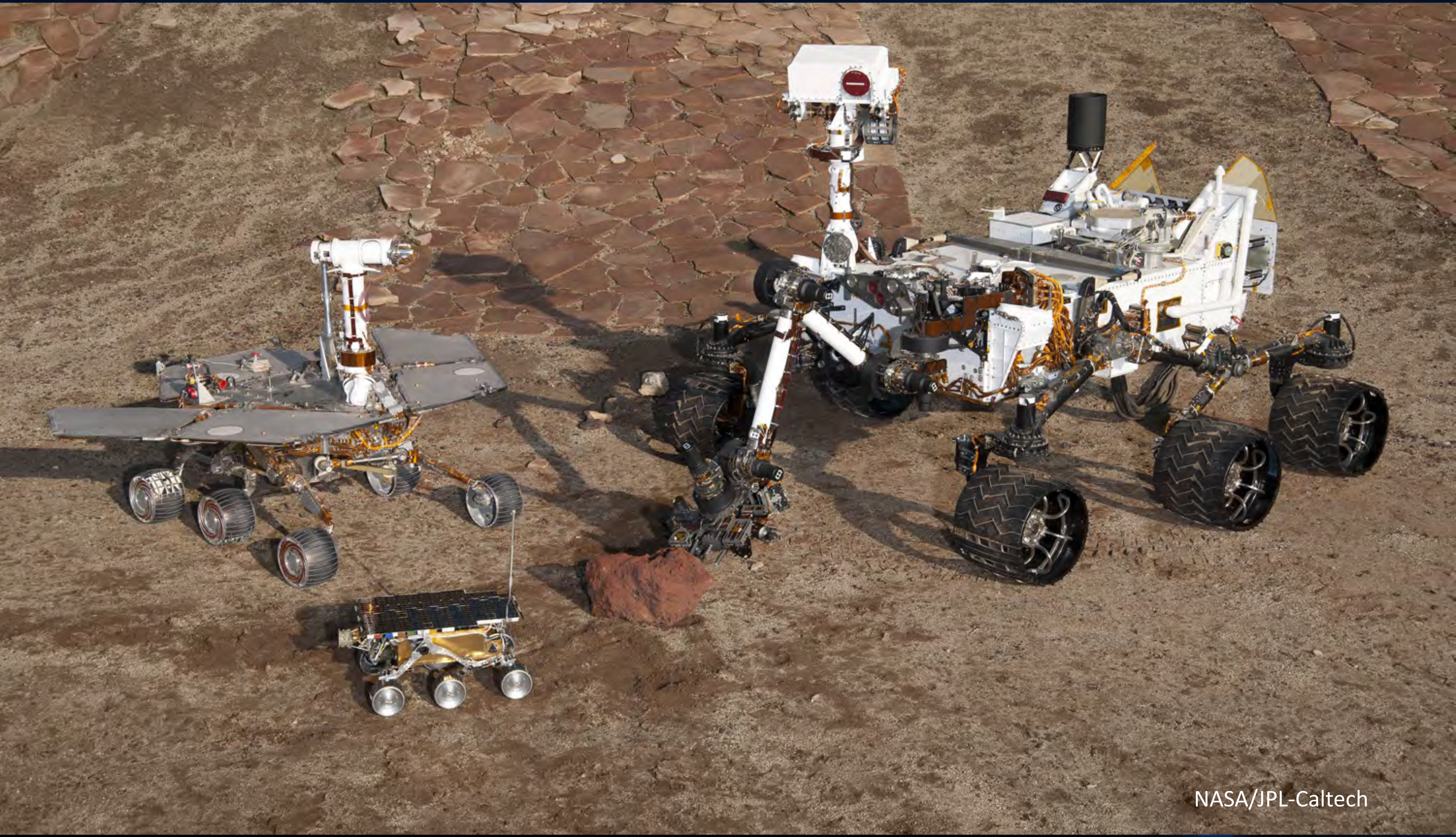
Evolution of Mars Rover Surface Navigation Autonomy

Mark Maimone
Jet Propulsion Laboratory
California Institute of Technology

Artist's Concept. NASA/JPL-Caltech

NESC GNC Webcast

Surface Autonomy Evolution



Research Rovers Go Way Back

SLRV (1964) (JPL and GM)

Blue Rover (1986)

Robby (1990)

Rocky 4 (1992)

NASA/JPL-Caltech

Courtesy Issa Nesnas

JPL Stereo Vision

Robotics Development: Rover Stereo Vision

Rover Stereo Vision

NASA - Planetary

1987-1989 | **1990** | **1991-92** | **1992-96** | **1997** | **1997-2001** | **2003**

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)

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

<u>"Robby"</u>
100M traverse by Mars rover testbed

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

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

<u>Mars Pathfinder</u>
Fast mapping enabled of terrain around lander; mission planning critical

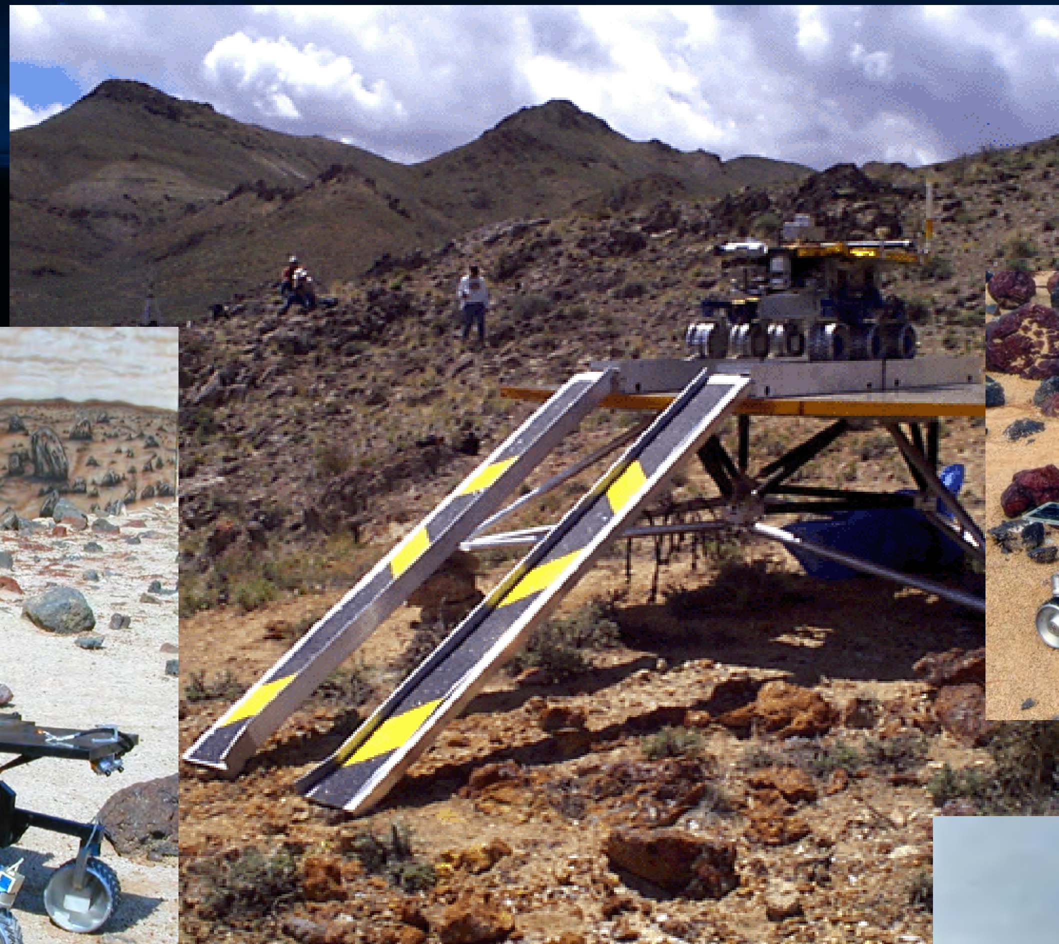
<u>ARL DEMO III</u>
Maintained core competency in real-time stereo vision for autonomous navigation

<u>MER</u>
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

Rovers in 2001



NASA/JPL-Caltech

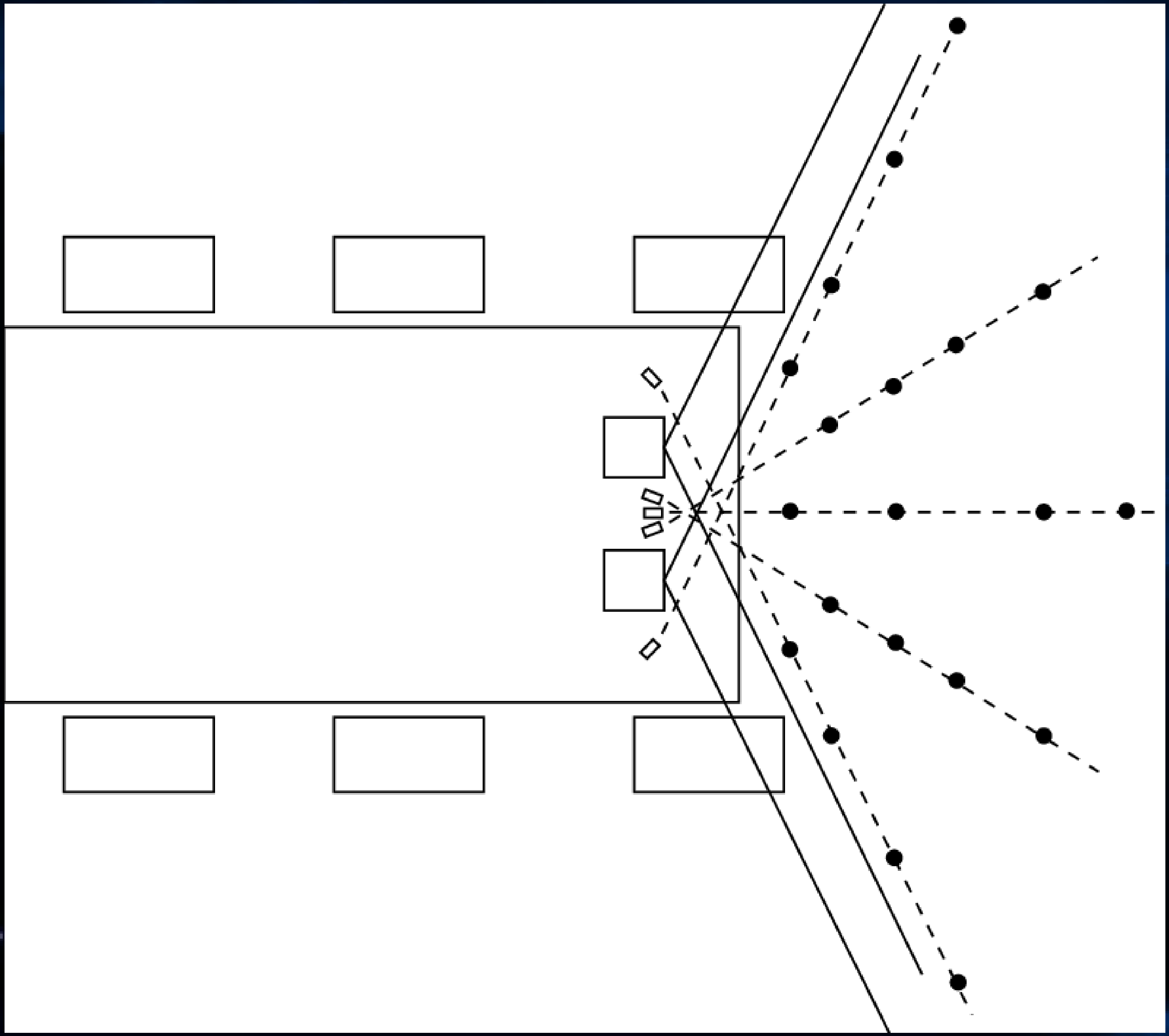
MER Autonomy Focus in 2000

Dense Stereo Vision

Autonomous Terrain Assessment

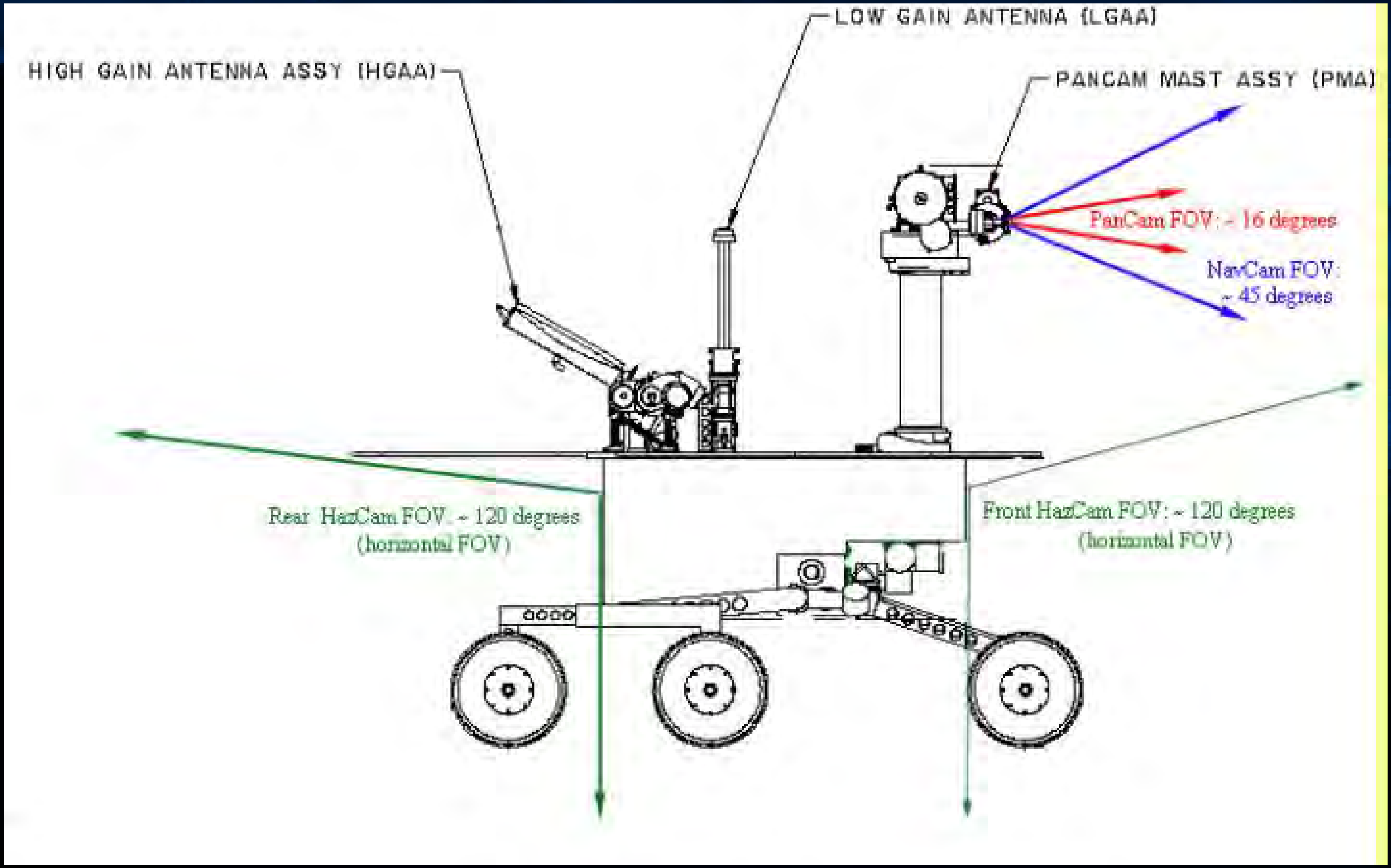
Autonomous Navigation

Sojourner Stereo Vision: 20 points



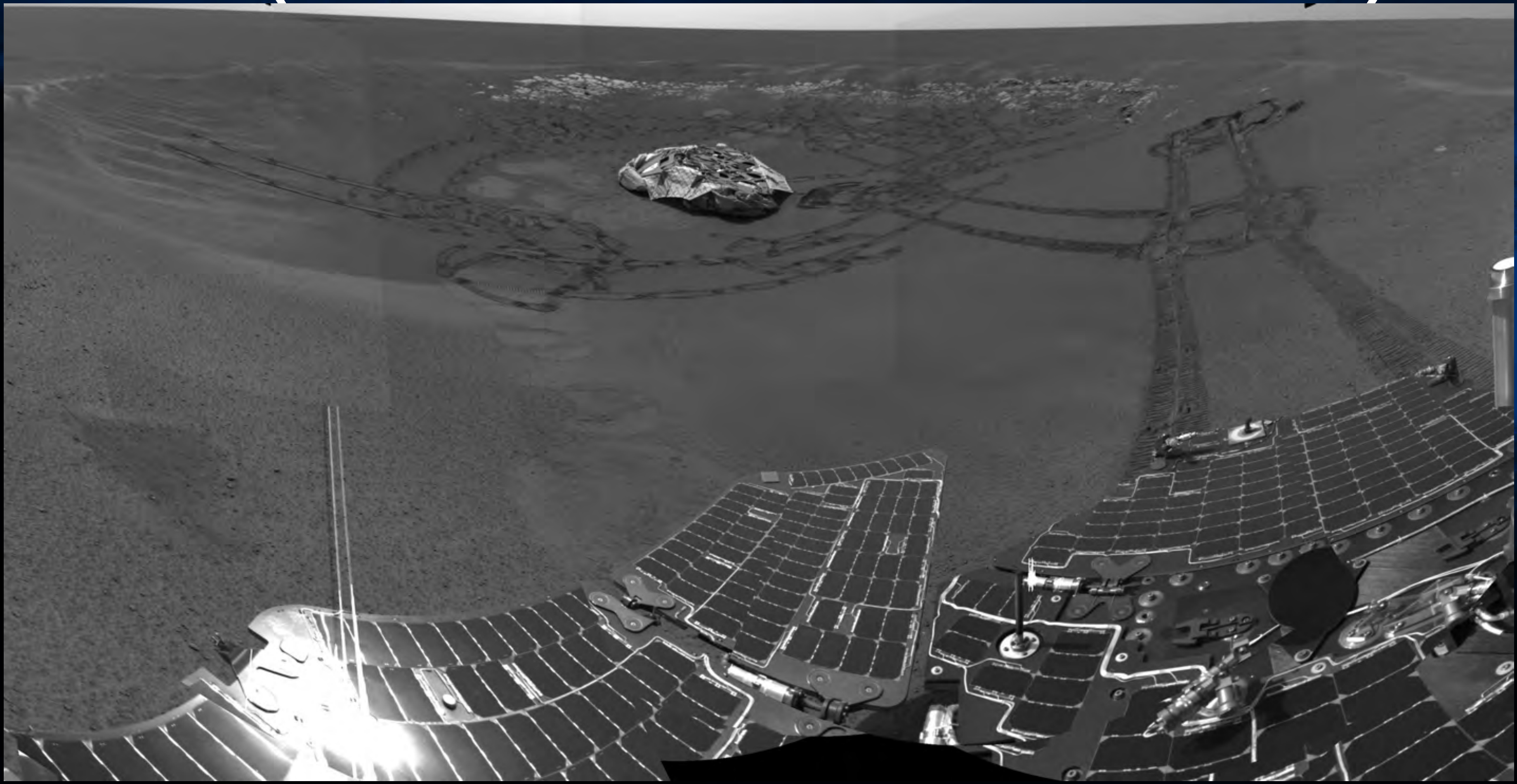
NASA/JPL-Caltech

MER Camera Fields of View



NASA/JPL-Caltech

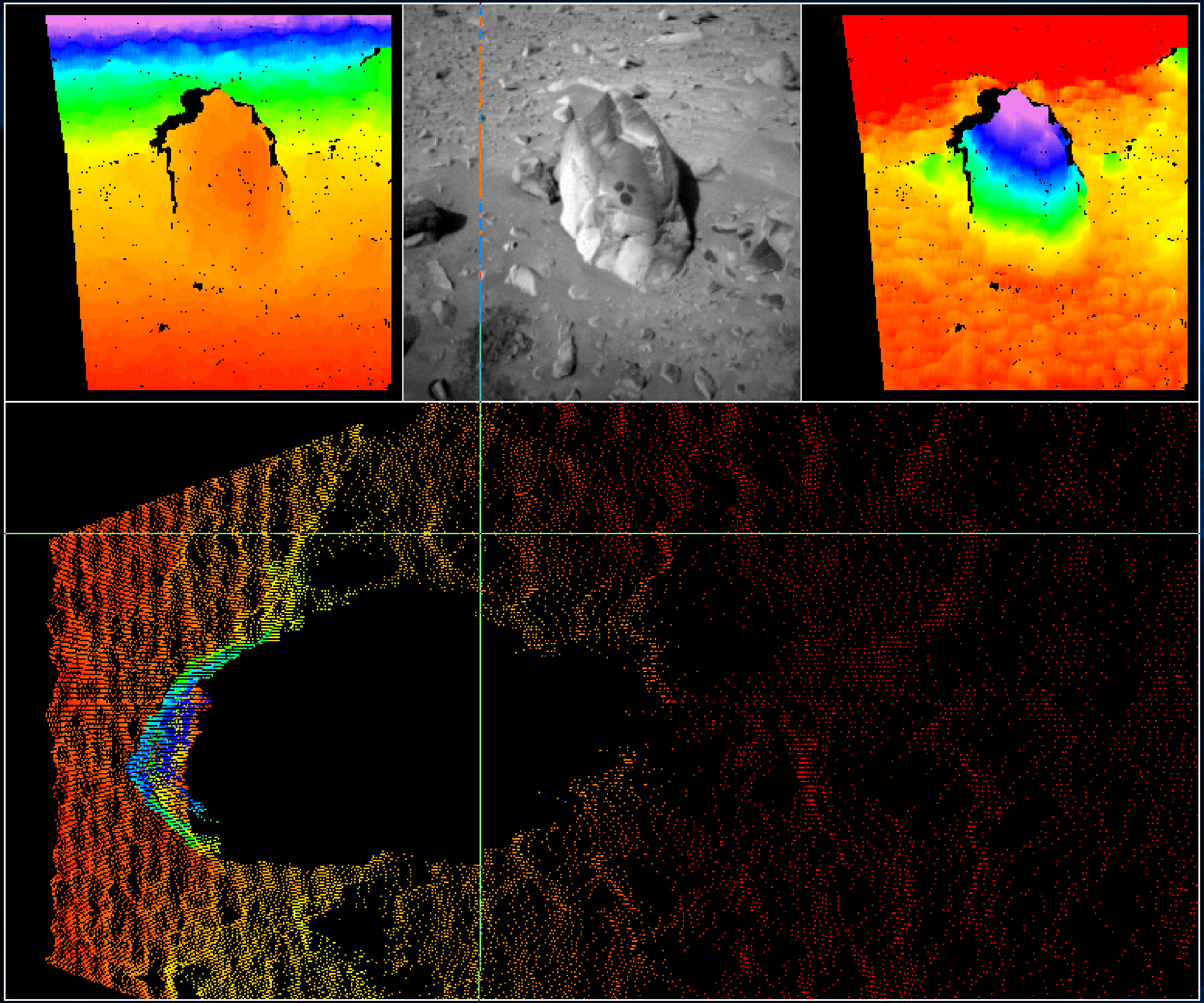
Lesson Learned: Expect the Unexpected (Hazcams fail to see terrain at low res)



Opportunity in Eagle Crater

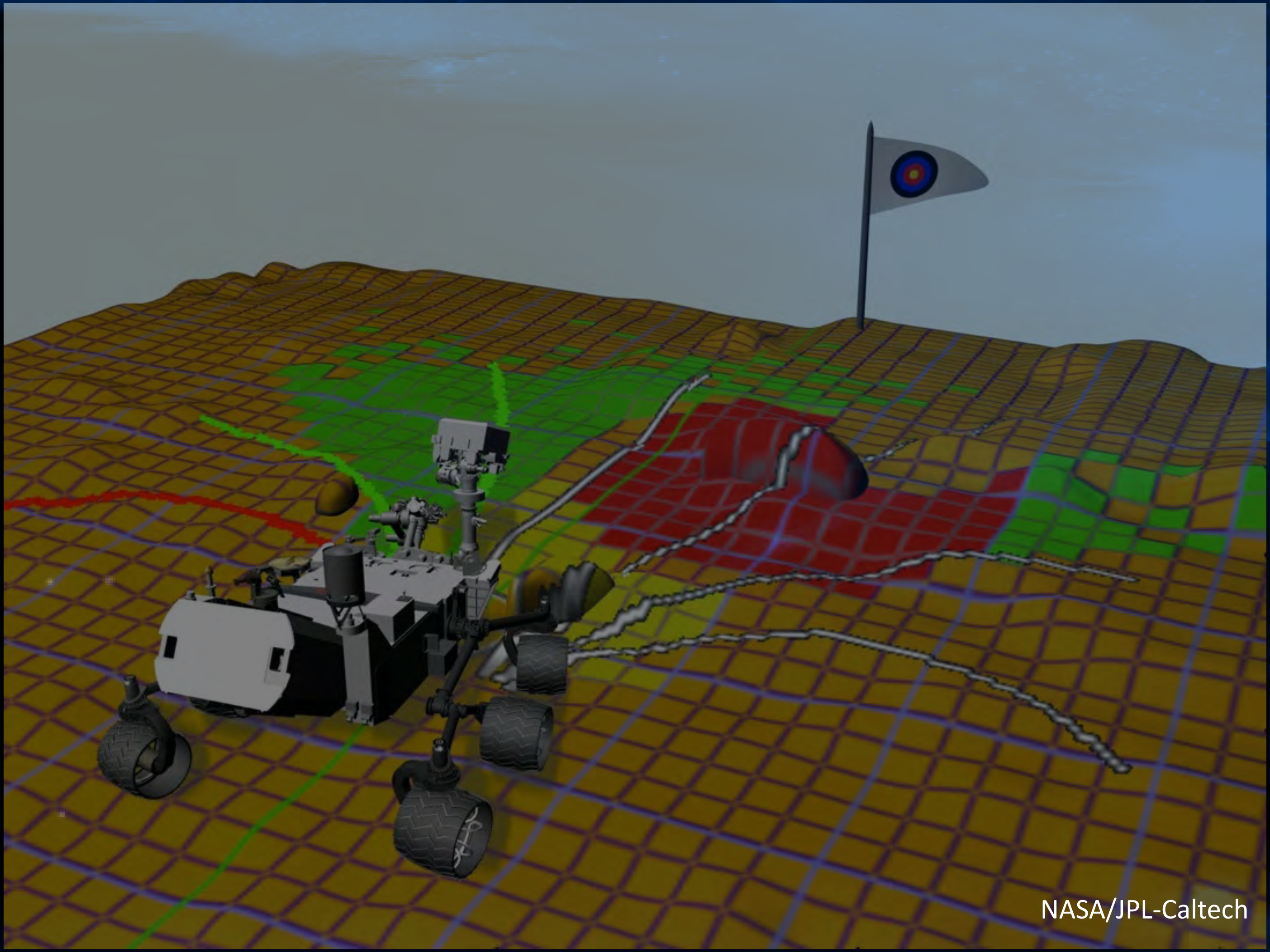
NASA/JPL-Caltech

Onboard Dense Stereo: MER, MSL, M2020

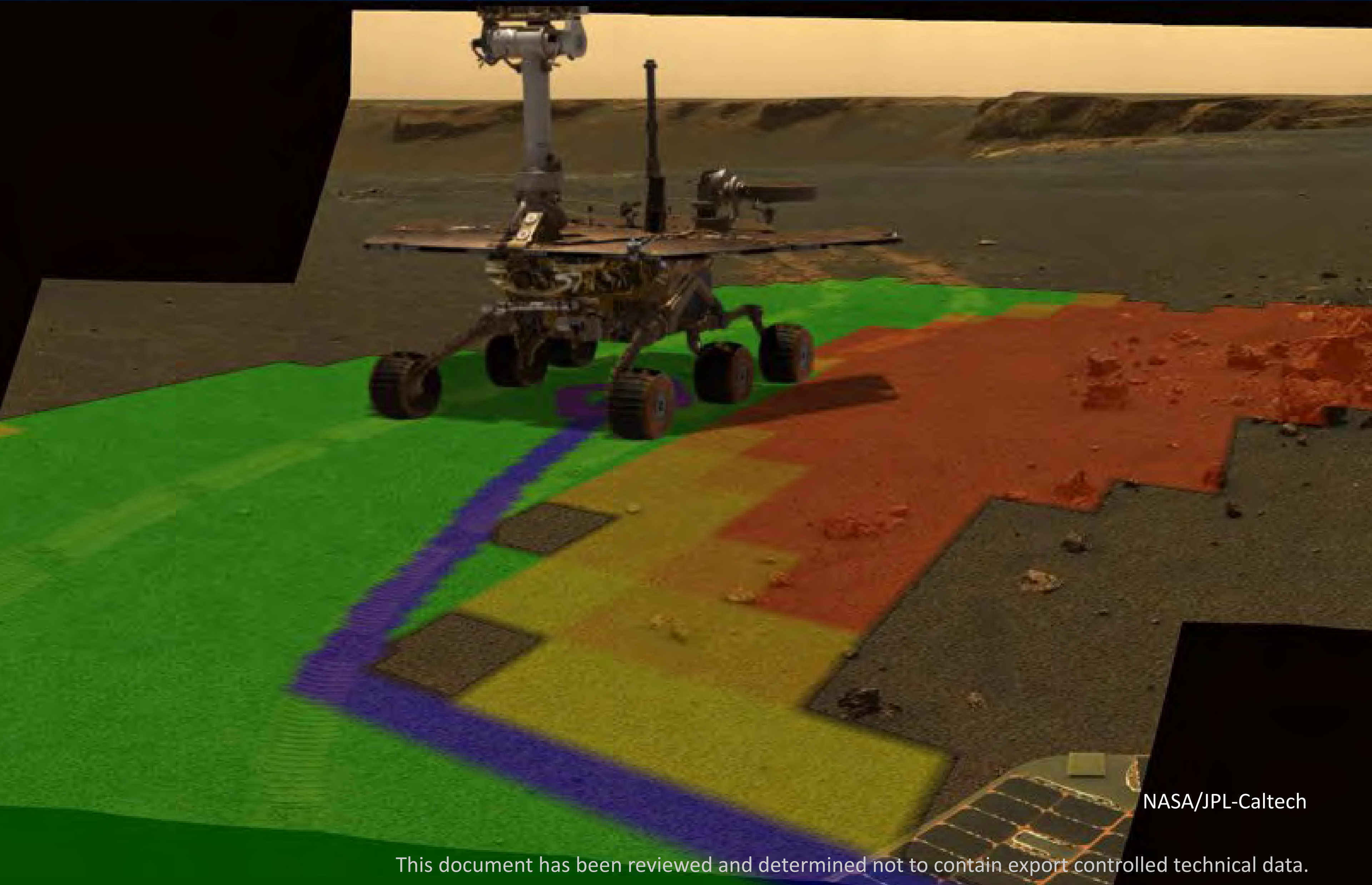


NASA/JPL-Caltech

Watch "Rover Navigation 101" online for deets.



GESTALT Terrain Analysis: MER, MSL



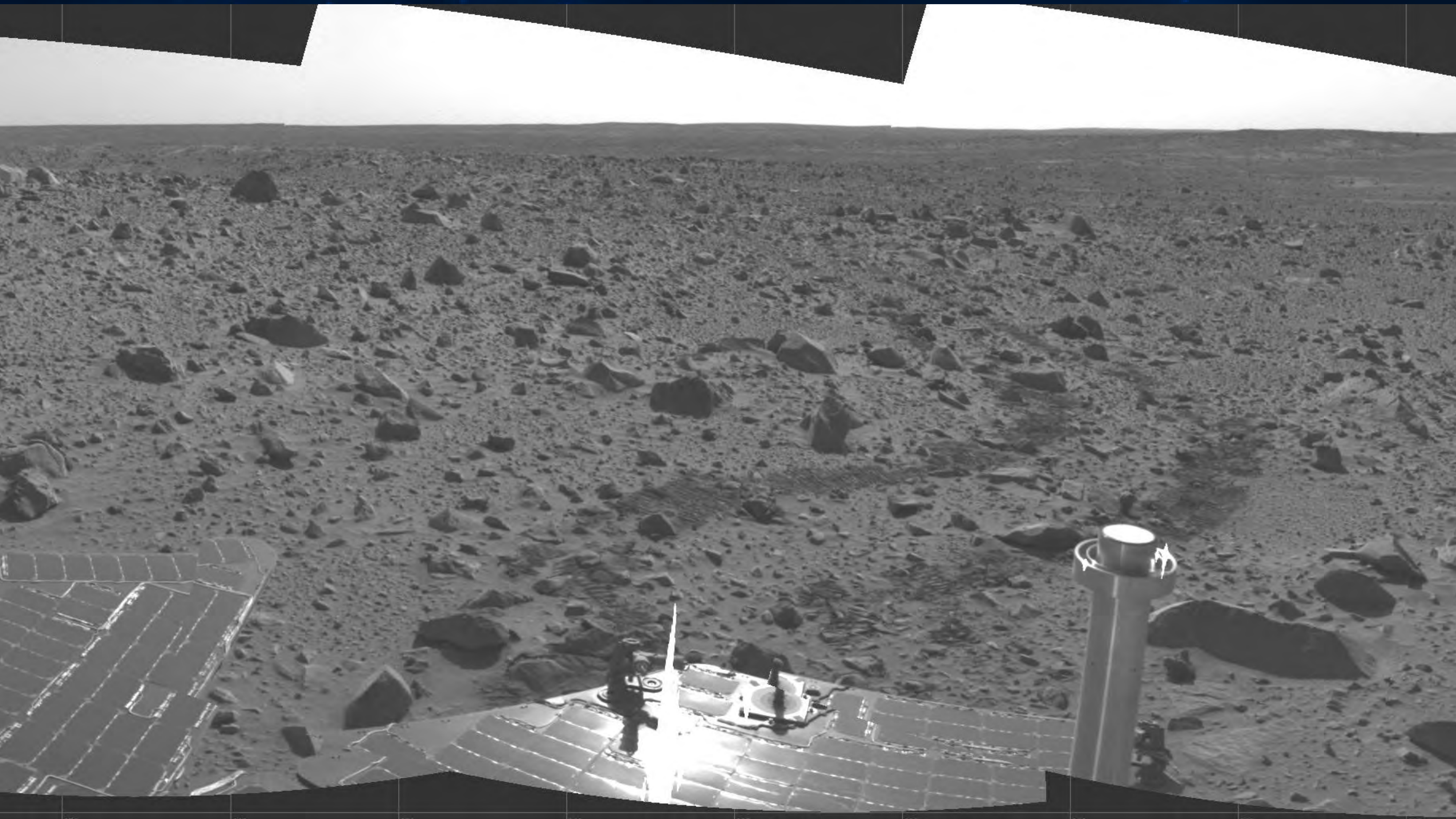
NASA/JPL-Caltech

Evolution of Flight Rover Specs

	Sojourner 1997	MER 2004	MSL 2012	M2020 2021
CPU	80C85	BAE RAD6000	BAE RAD750	BAE RAD750 (x2) FPGA Xilinx Virtex5QV
MHz	2	20	133	133 (x2) + FPGA (22M disp/s)
RAM (Mbytes)	0.56	128	128+512	128 (x2) + 512 (x2)
Non-volatile storage (Mbytes)	0.17	256 flash	4,096 flash	4,096 + 3,072 flash
Image Pairs/Step	1	1-2	4	1
Stereo Pixels processed per step	20	10,000 - 50,000	40,000 - 200,000	FPGA: 240,000 – 1,200,000
Autonav Pause/Step (seconds)	?	~120	~120	< 14

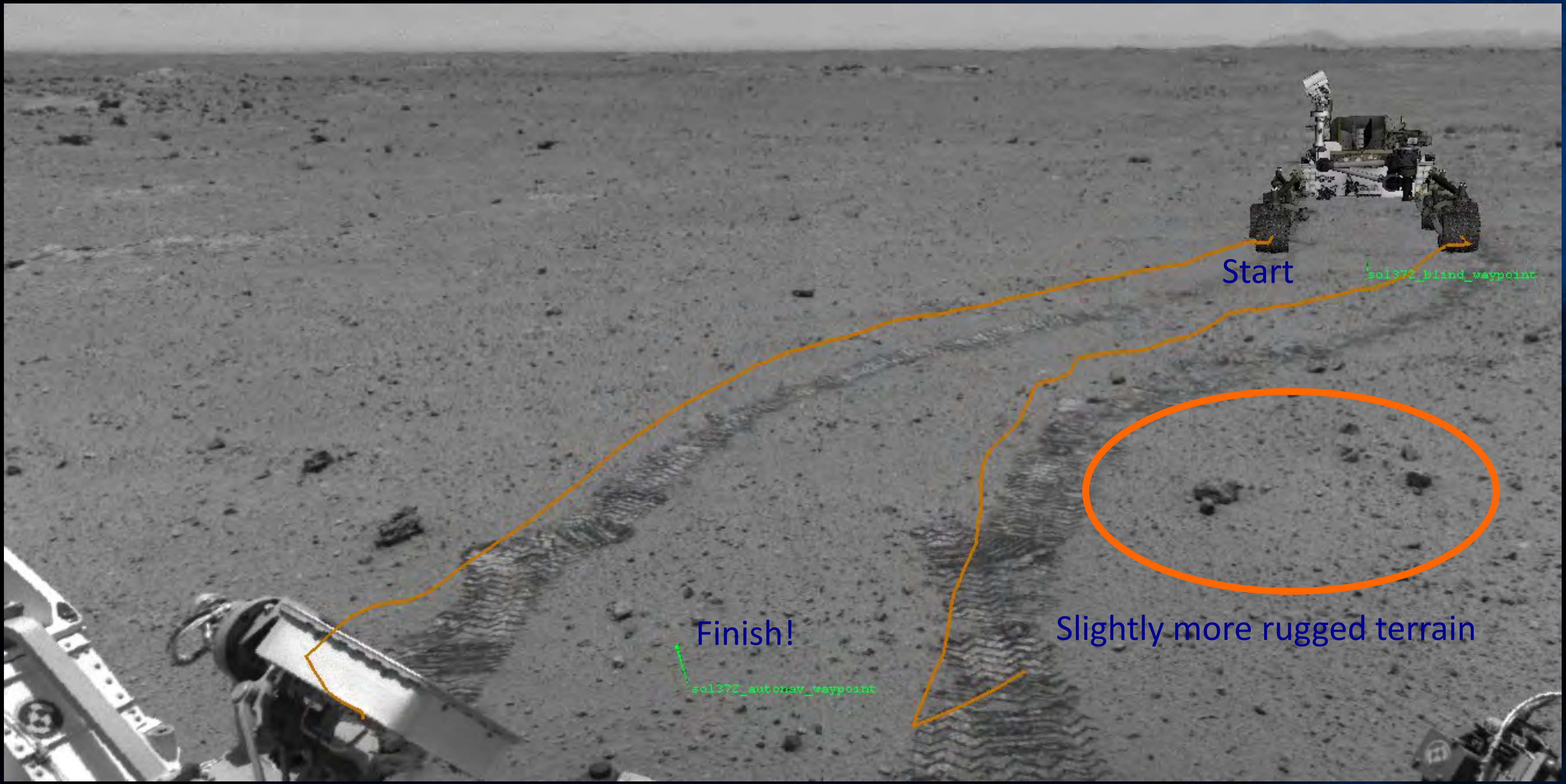
Spirit Sol 106: Avoiding a 21cm rock

Spirit Sol 107: Avoiding Rock Pile



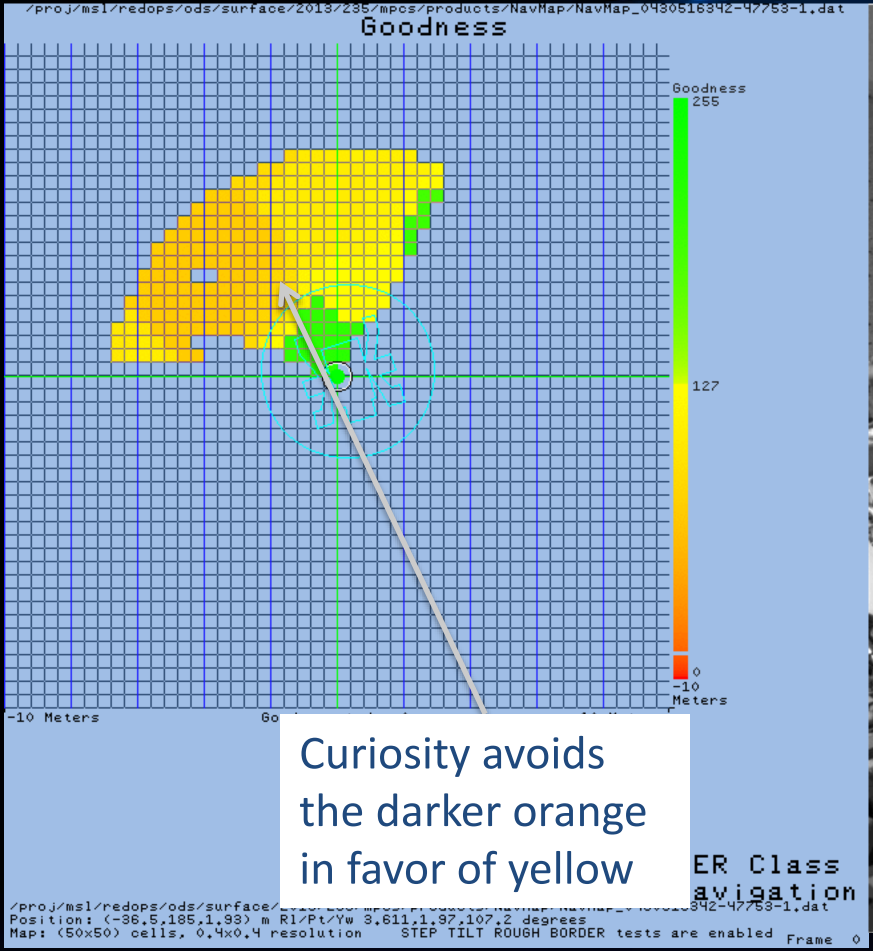
NASA/JPL-Caltech

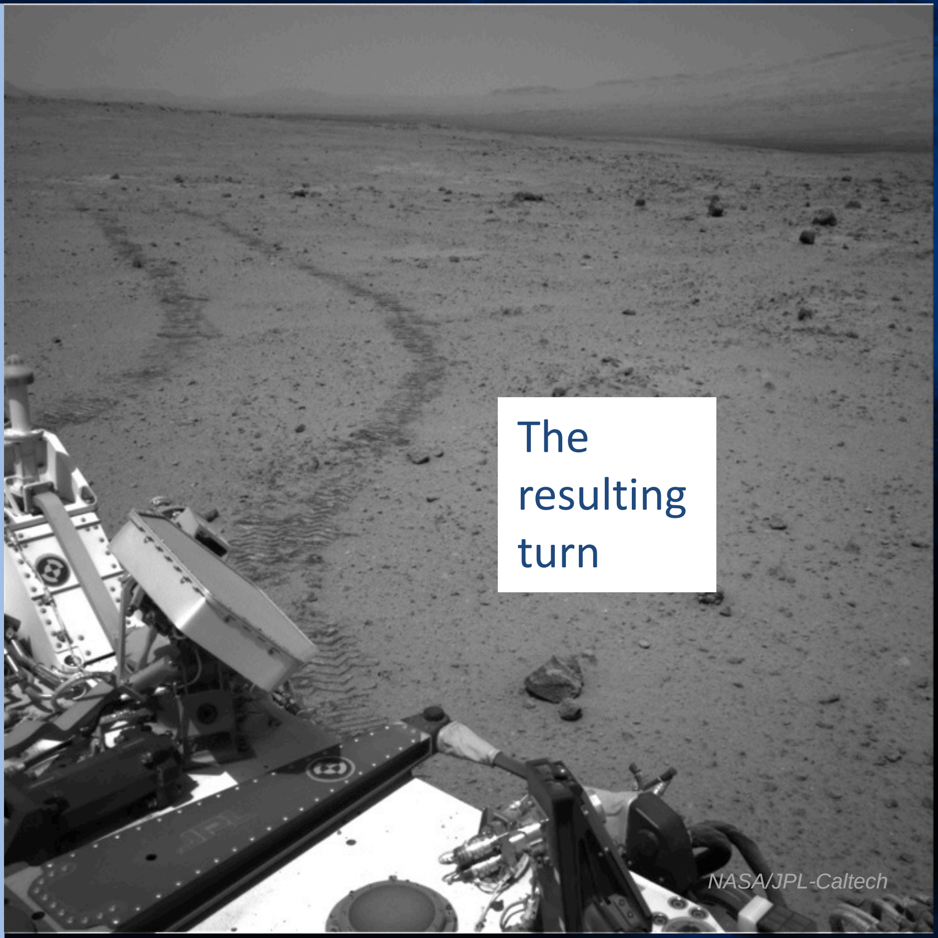
Wheel tracks after the first auto-nav drive on sol 372 show that Curiosity chose to drive around a little mound of loose rock.



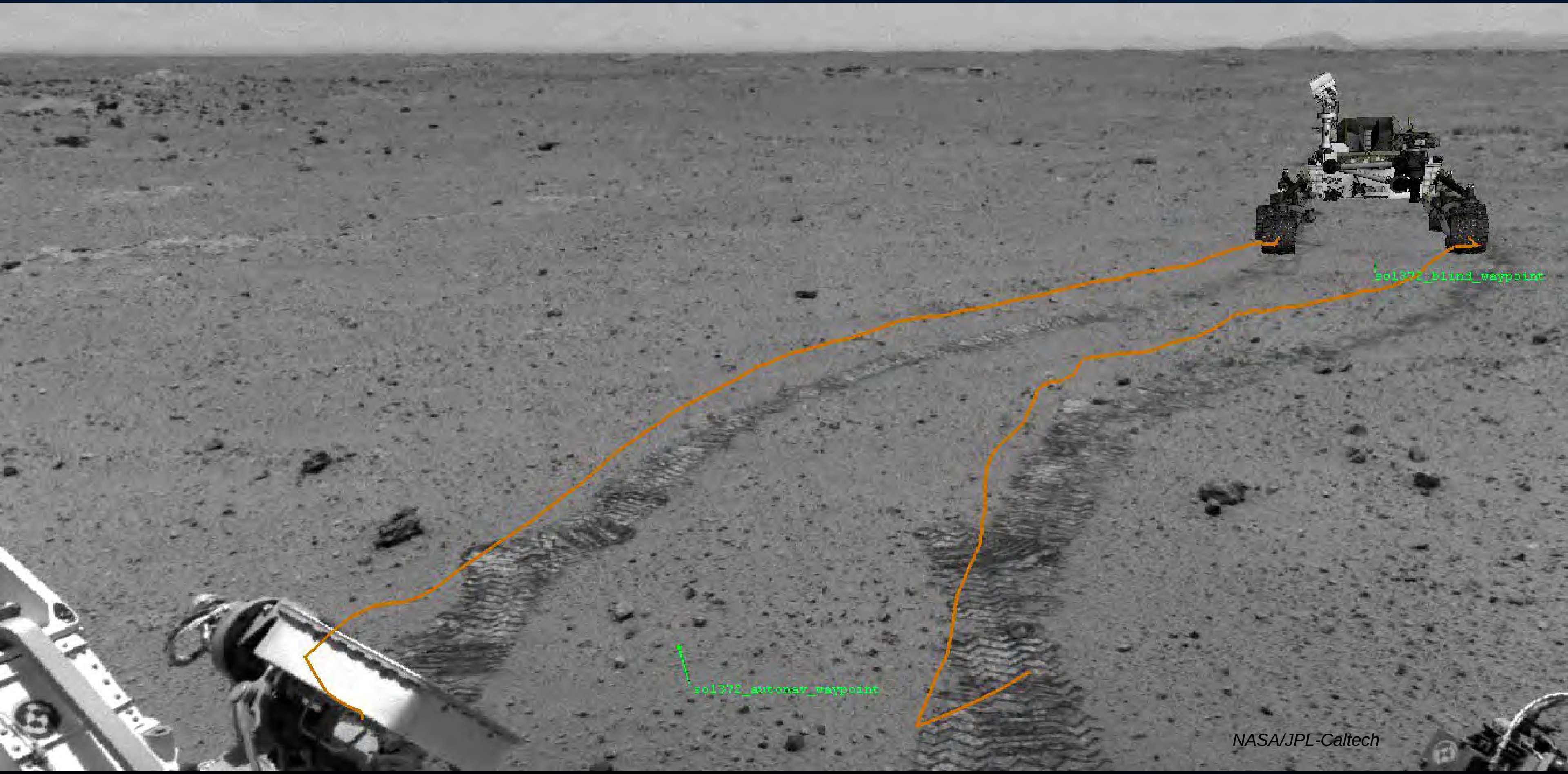
NASA/JPL-Caltech

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



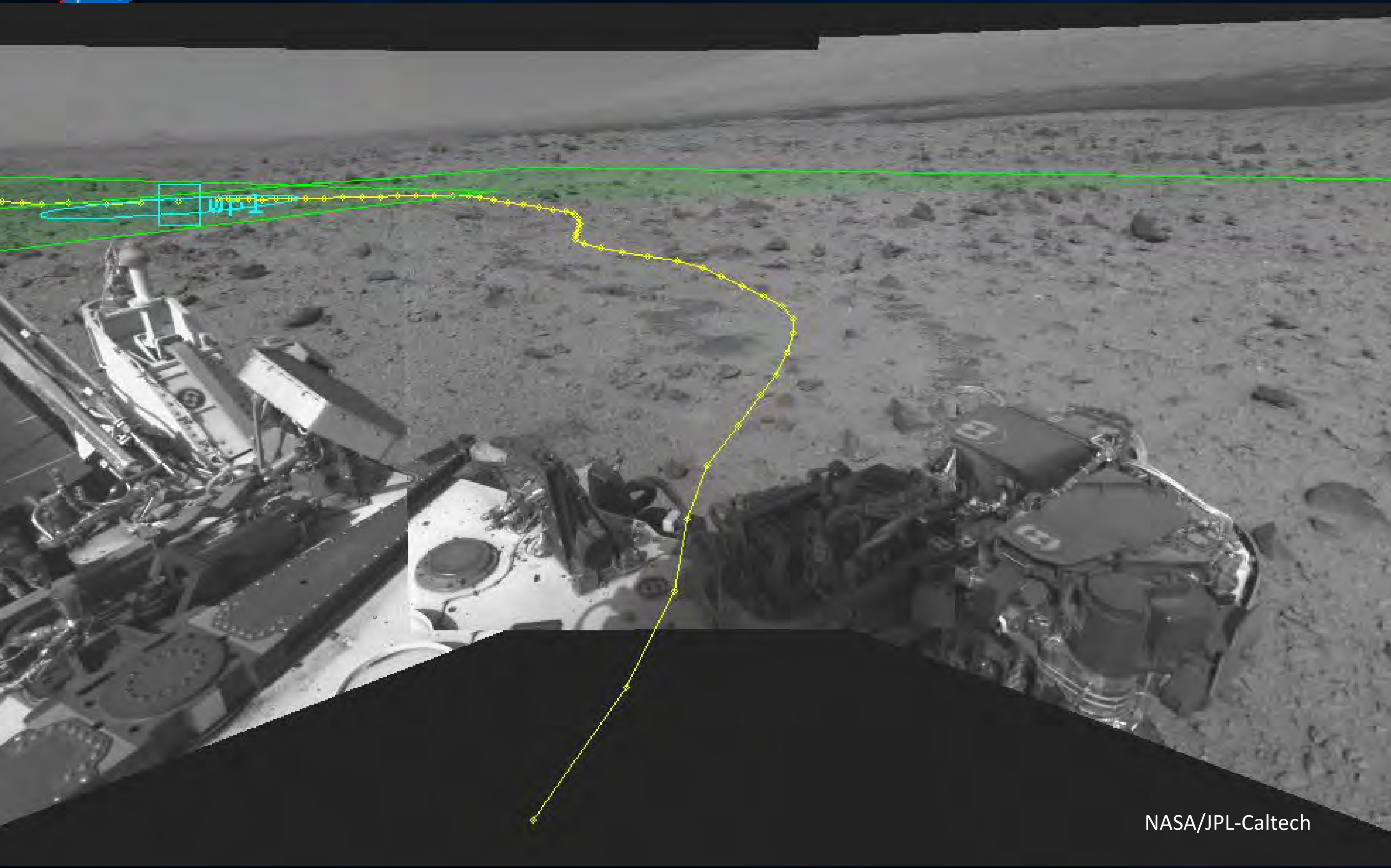


Animation of Curiosity's actual Sol 372 drive over a picture of her tracks

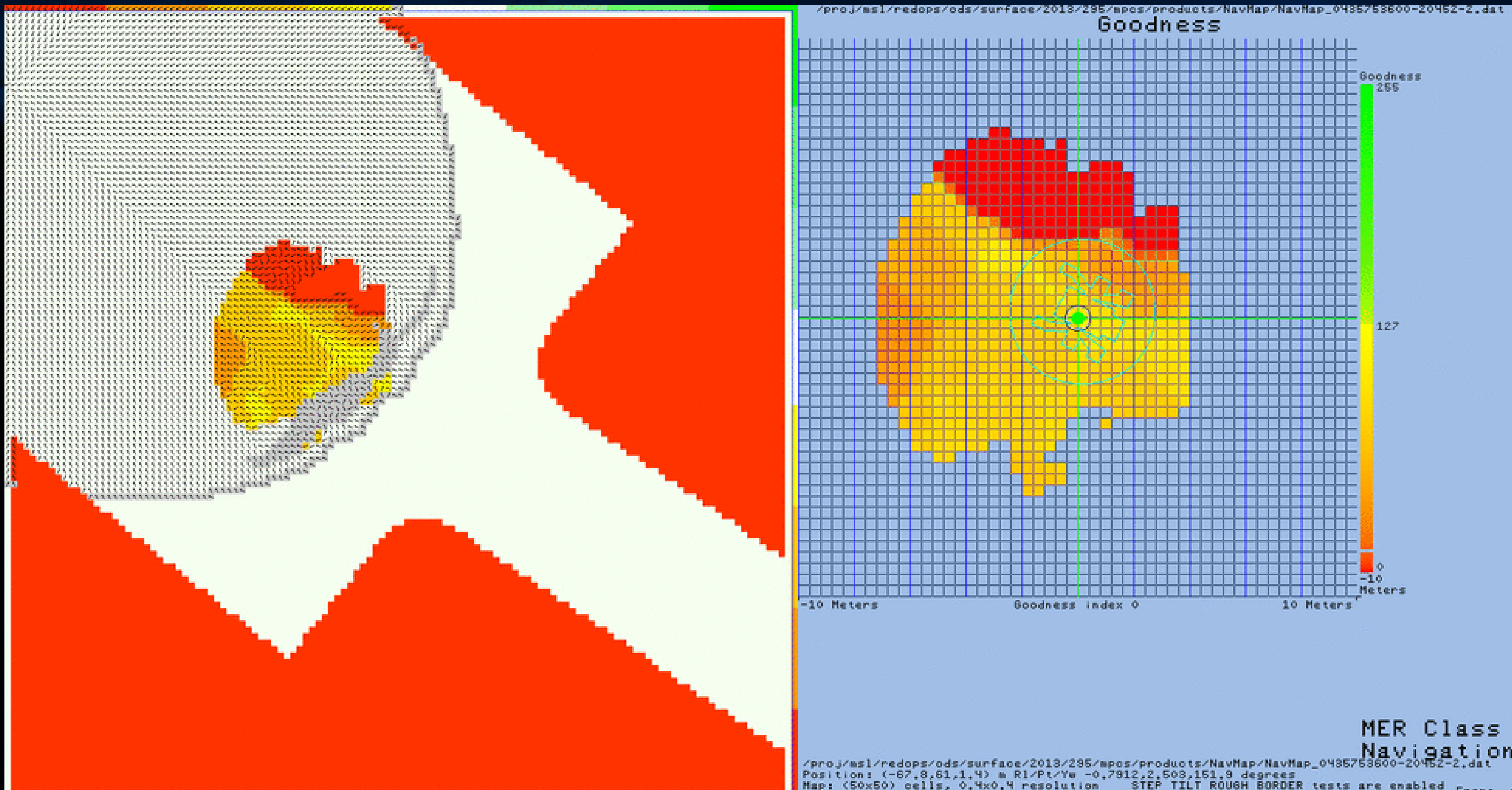


Finish!

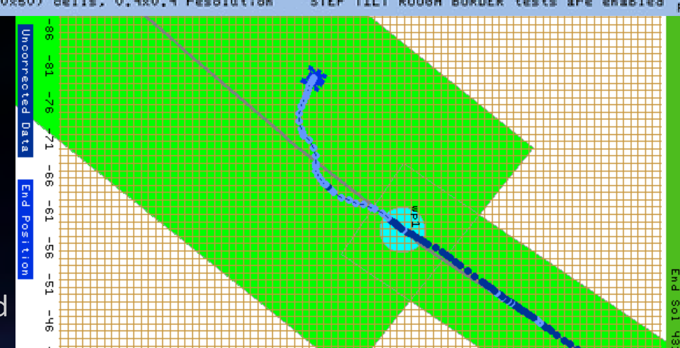
Curiosity Sol 431: Avoiding Rocks



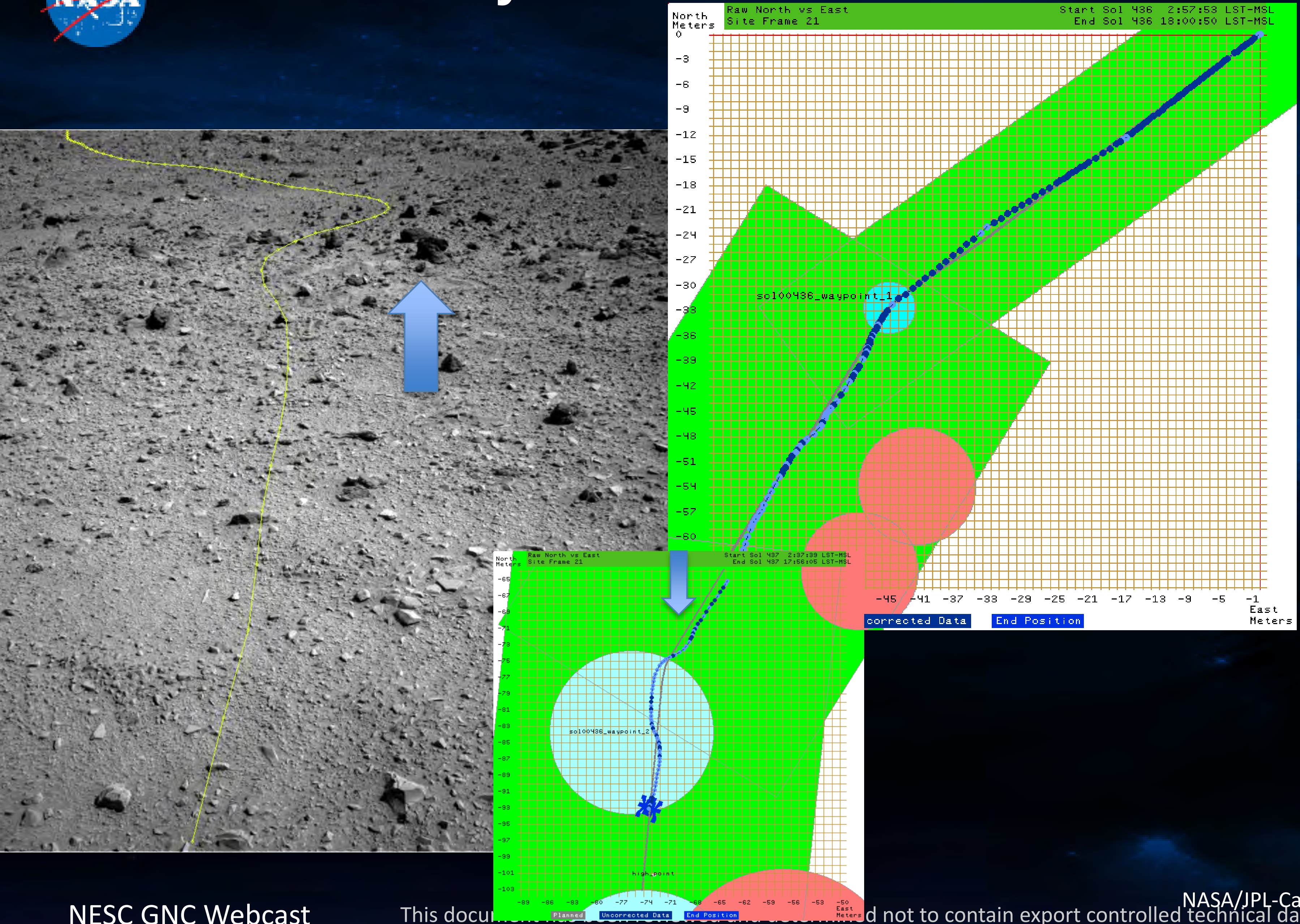
Curiosity Sol 431: Avoiding Rocks



NASA/JPL-Caltech



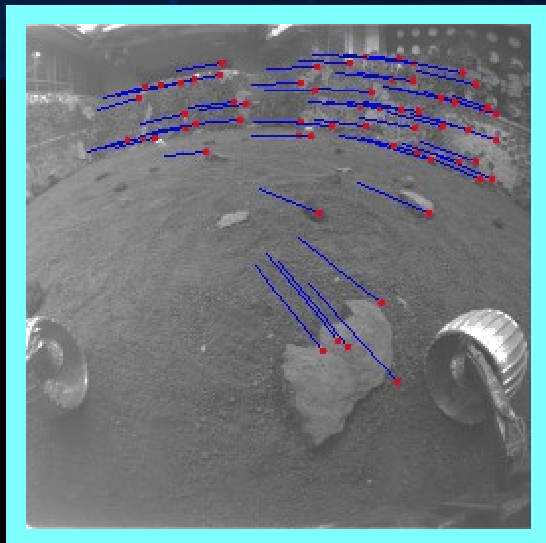
Curiosity Sol 436-437: Multi-sol Drive



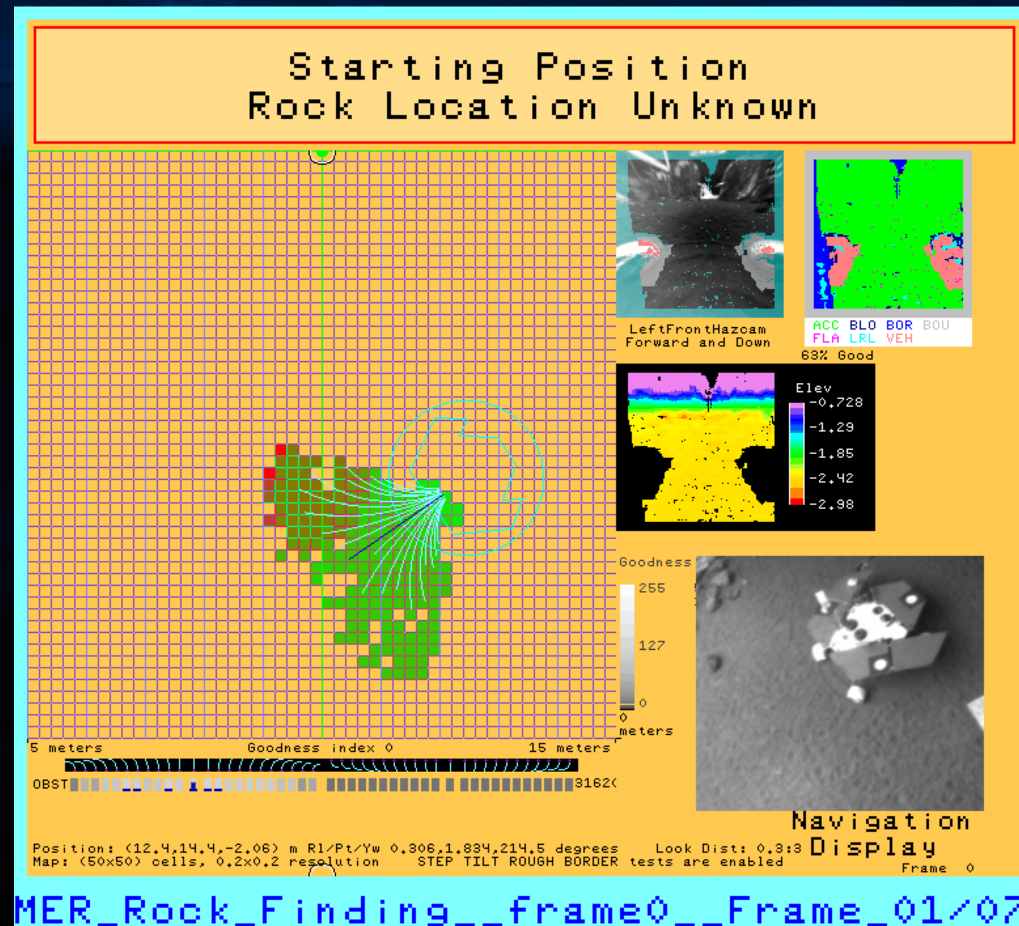
NASA/JPL-Caltech

Post-launch Autonomy "Extras"

Visual Odometry



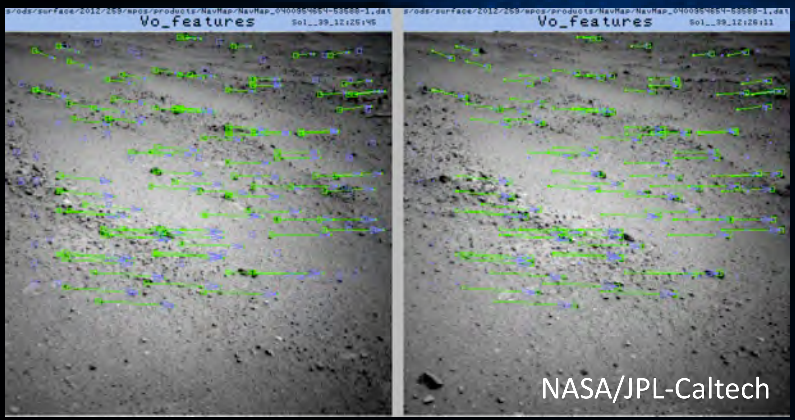
Guarded Motion

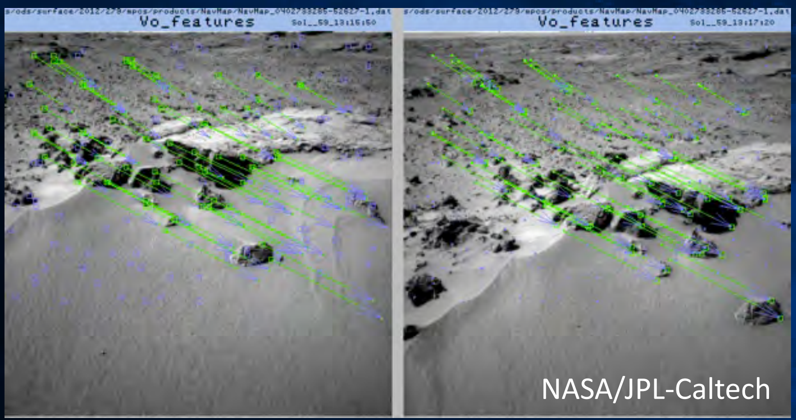


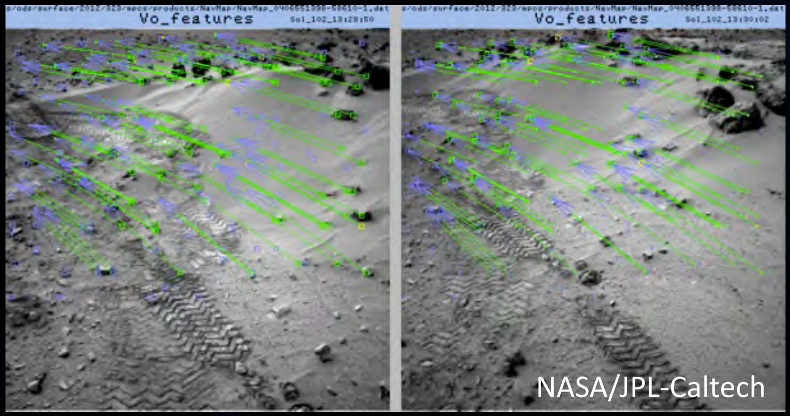
Turn To a Rock, Go To a Rock

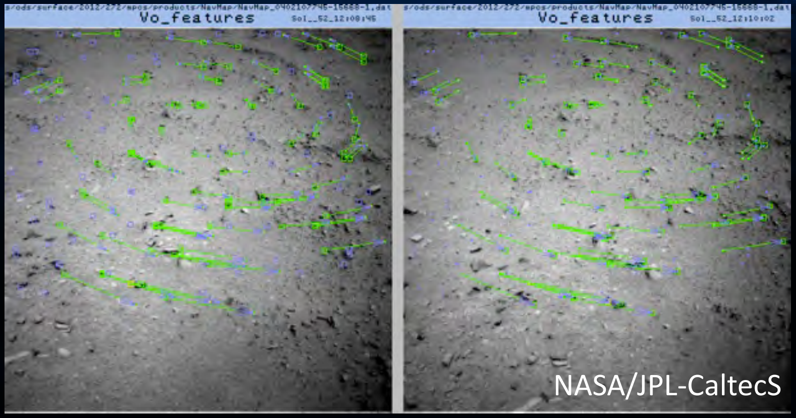
NASA/JPL-Caltech

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



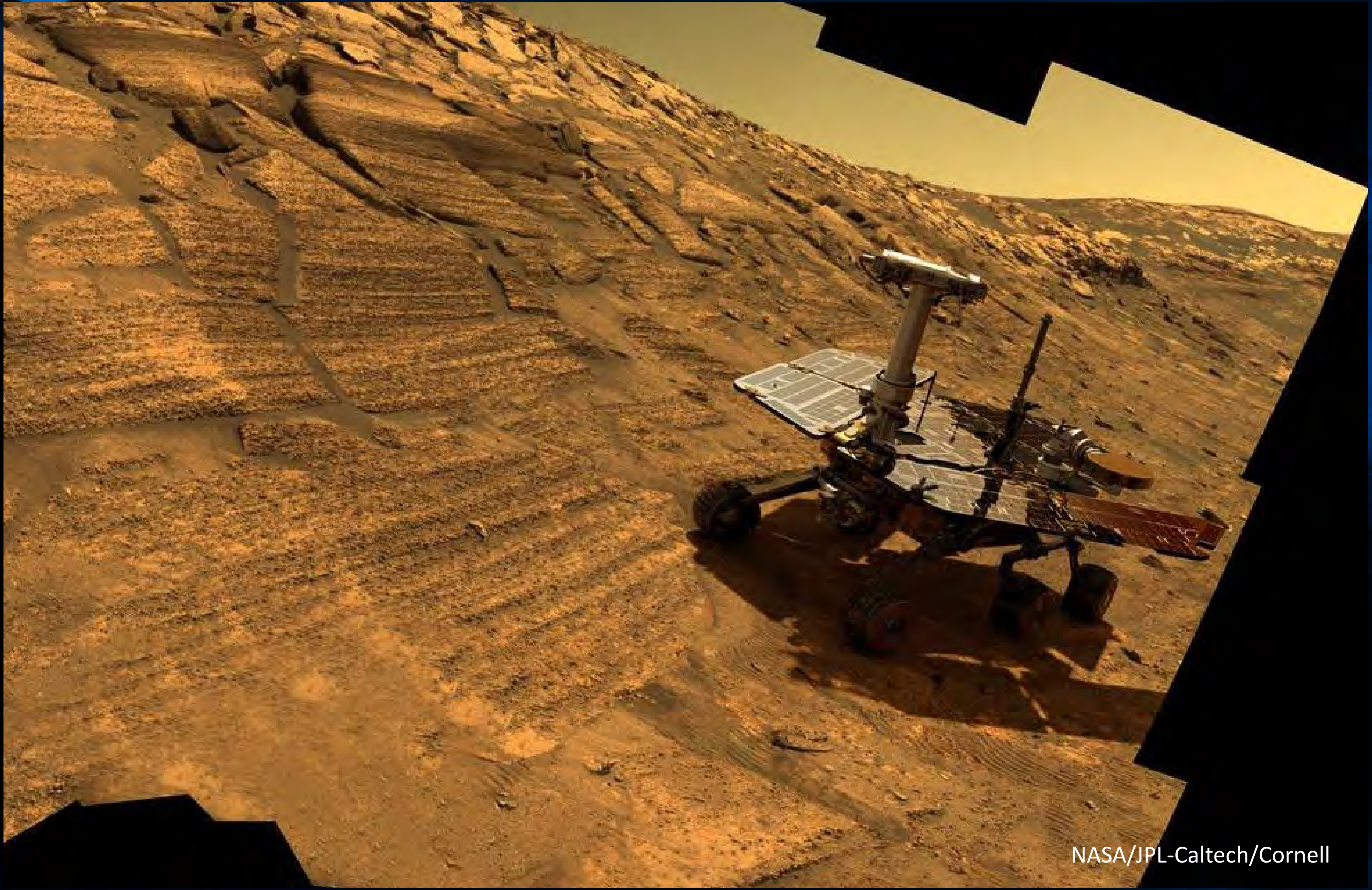




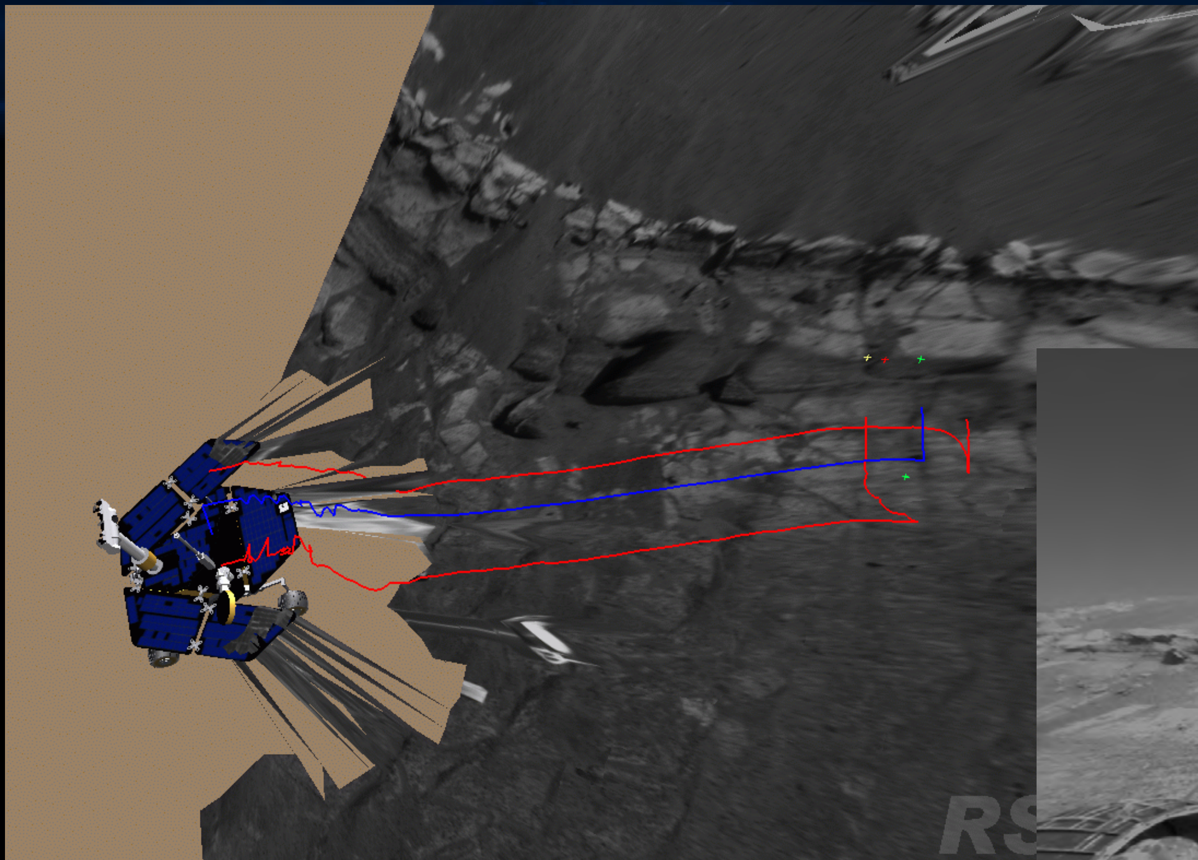


Unlike terrestrial robots, Curiosity drives as far as possible between VO images

VO is helpful on Slopes



VO Enables Fewer Approach Sols



NASA/JPL-Caltech

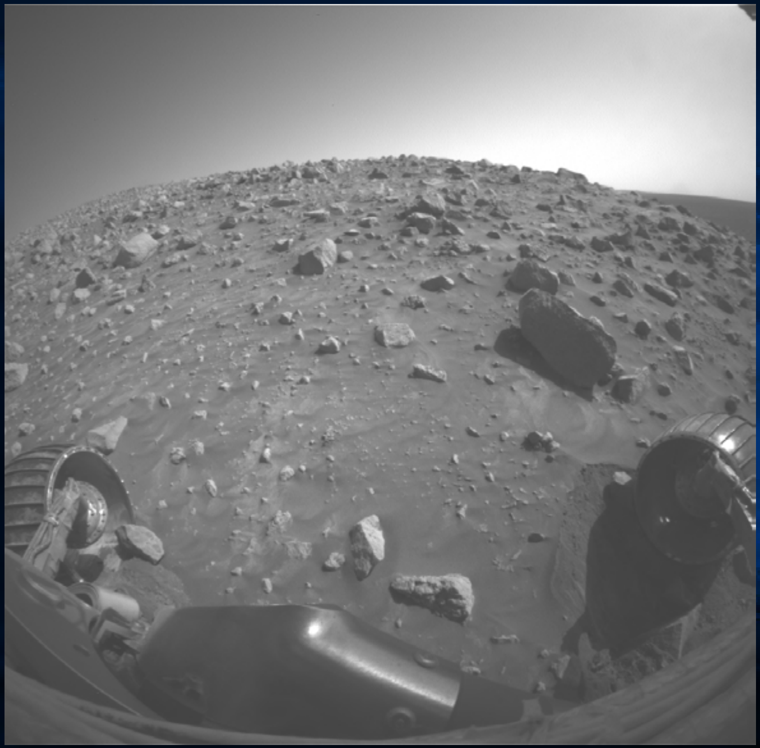
VisOdom enabled 8 meter 1-sol approach on 20-24 degree slope

Spirit's terrains benefit from VO

Why We Need VO: Unpredictable Slip

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

Lesson Learned: Spirit Slip Check



On A-345, Spirit stalled because a potato-sized rock had gotten wedged inside a wheel. Recovery time: 1 week.

On A-454, Spirit detected 90% slip and stopped with rocks poised to enter the wheel. Recovery time: 1 day.

NASA/JPL-Caltech

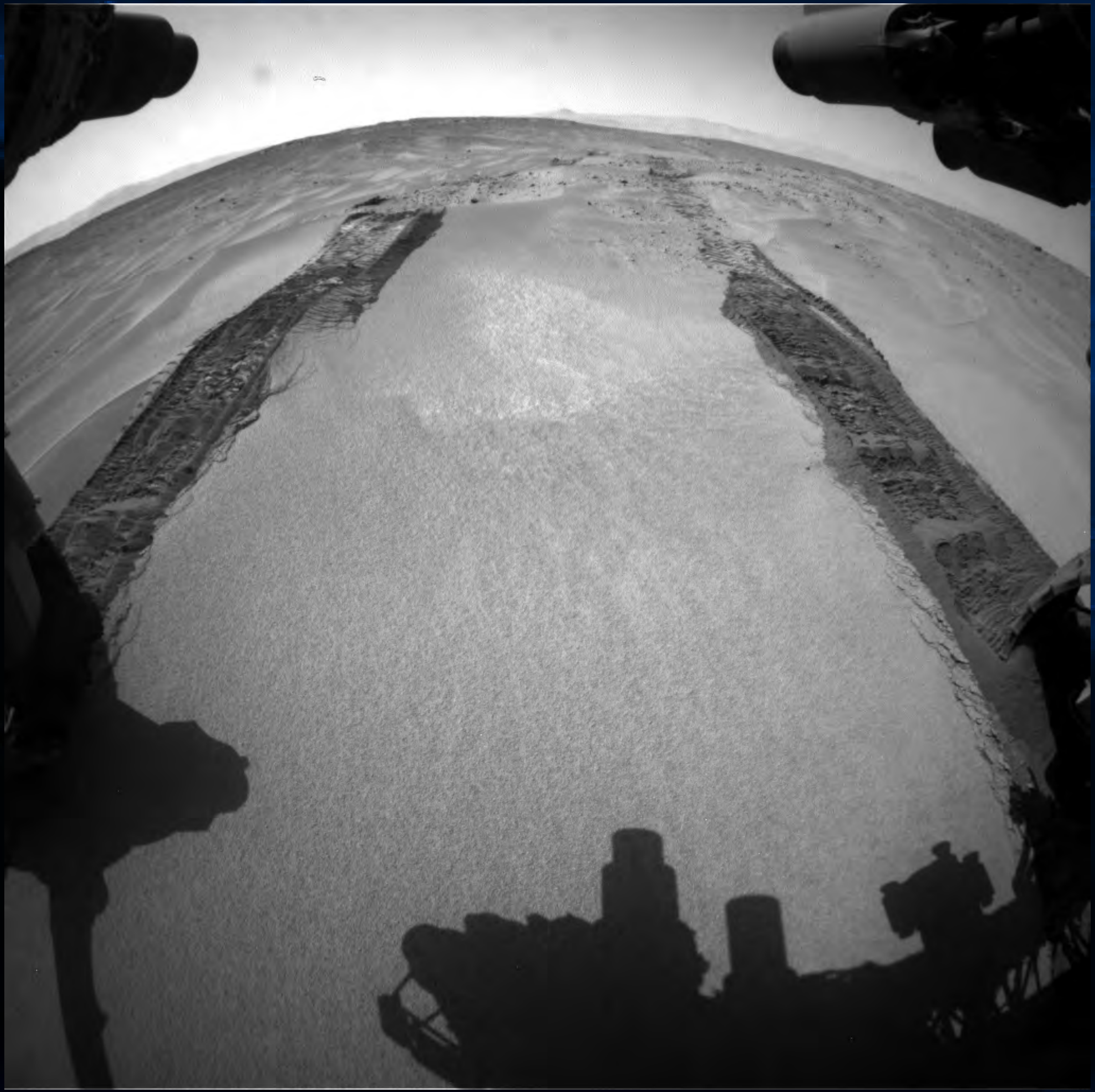
Opportunity Sol 446 Embedding

On B-446, 50 meters of blind driving made only 2 meters progress, burying the wheels. Recovery time: 5 weeks.

On B-603, 5 meters of blind driving made 4 meters progress (stopped by Visodom with 44% slip). Recovery time: 1 day.

NASA/JPL-Caltech

Curiosity Sol 672 Near-Embedding

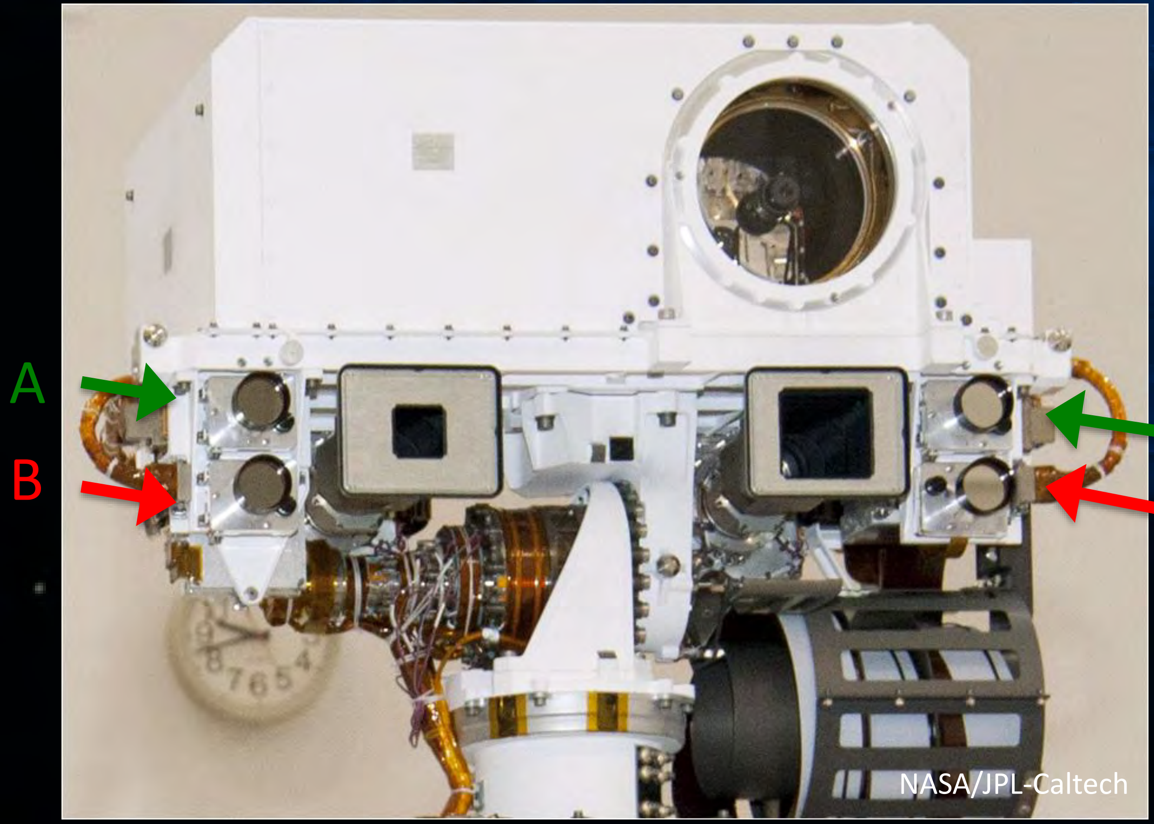


NASA/JPL-Caltech

Recovery Time: 1 day

Sol 201: Backup Navcams

When the B-side computer (RCE-B) became prime, Curiosity also switched to backup cameras

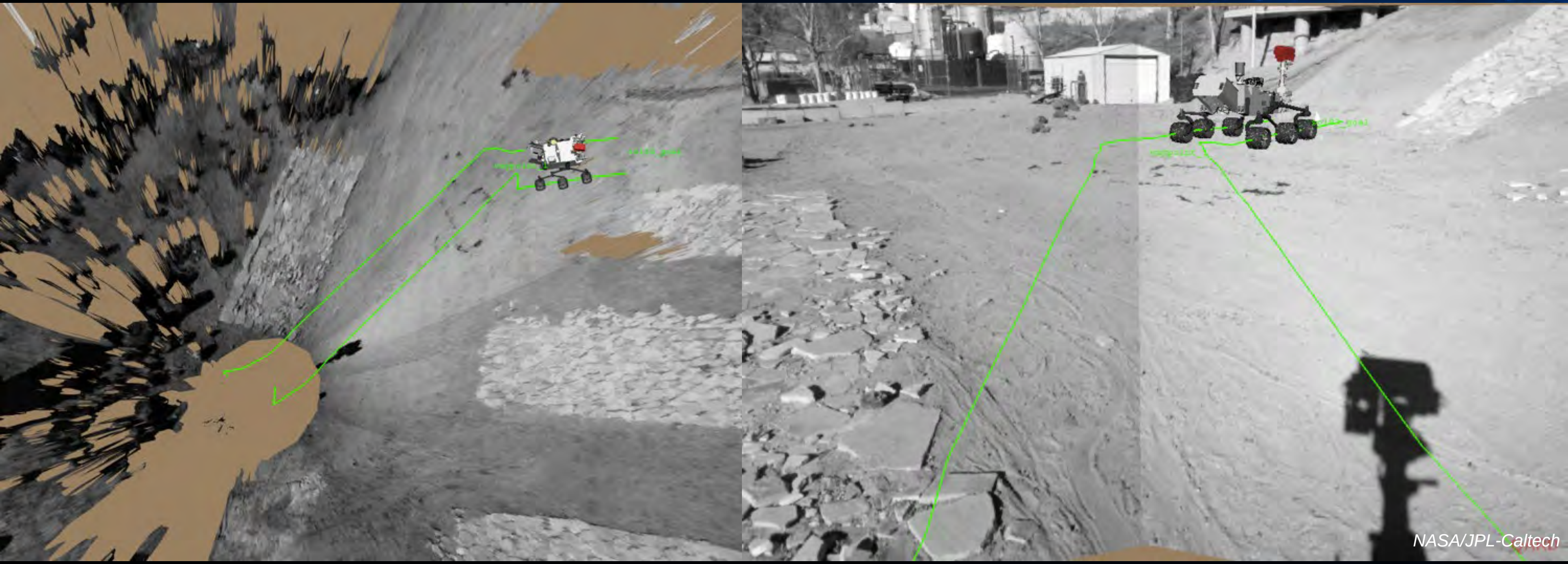


Unfortunately, the geometric lens models for the Navcams created before launch had poor stereo performance

Sol 201: Backup Navcams

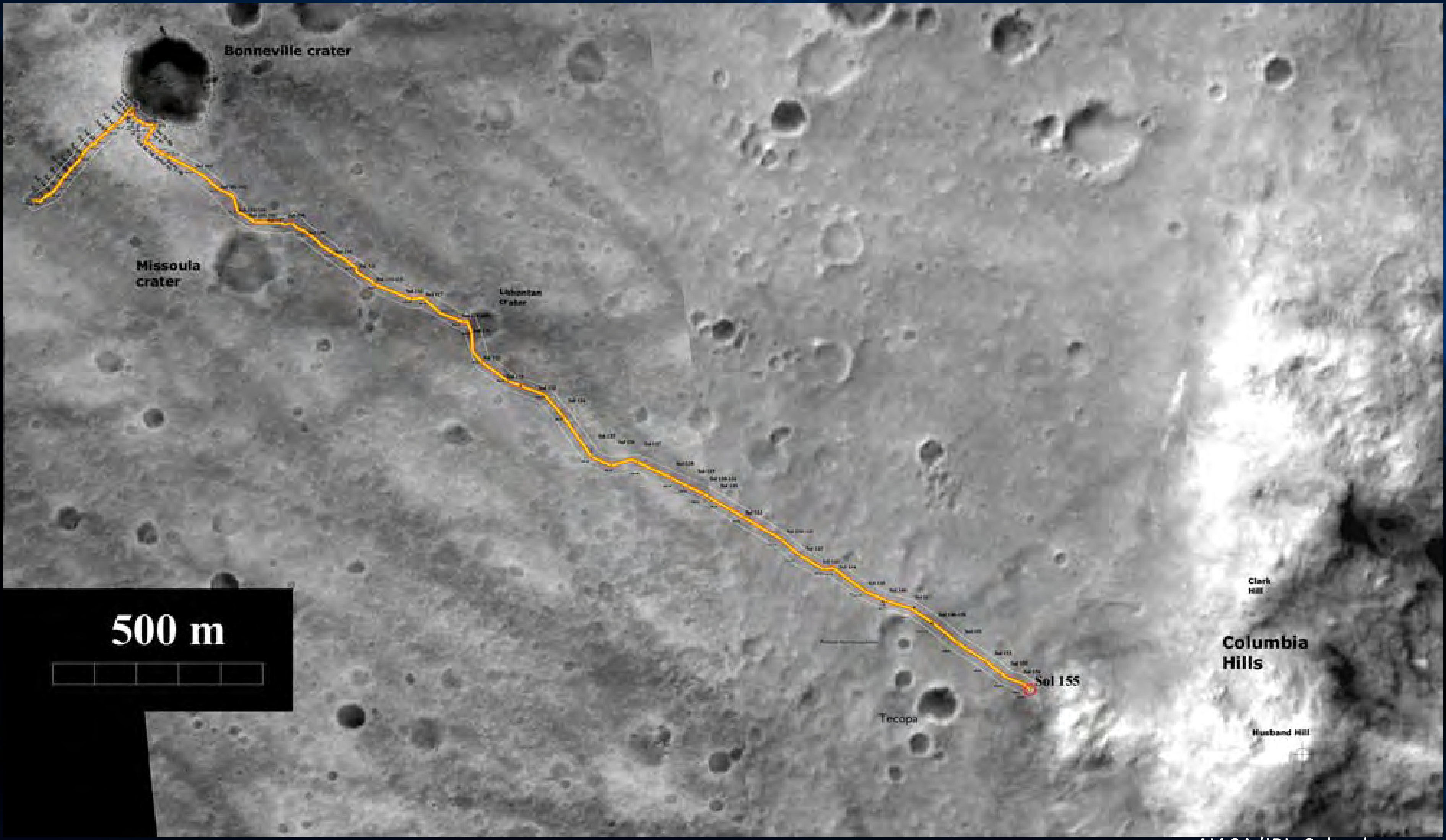
- It was ultimately determined that the cameras rotated slightly, but *predictably,* depending on the current temperature
- We developed a novel re-calibration procedure, and generated new models at 4 temperatures
- Ground software was updated to use the current temperature
- R10 flight software was patched to read the current temperature and use the correct camera models by command to restore onboard autonomous imaging capabilities
- R11 flight software was enhanced to support temperature-varying camera models autonomously

Human Rover Planners plan Nearby Drives



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

Spirit Drive through Sol 155



Spirit Drives through Sol 418

NASA/JPL-Caltech

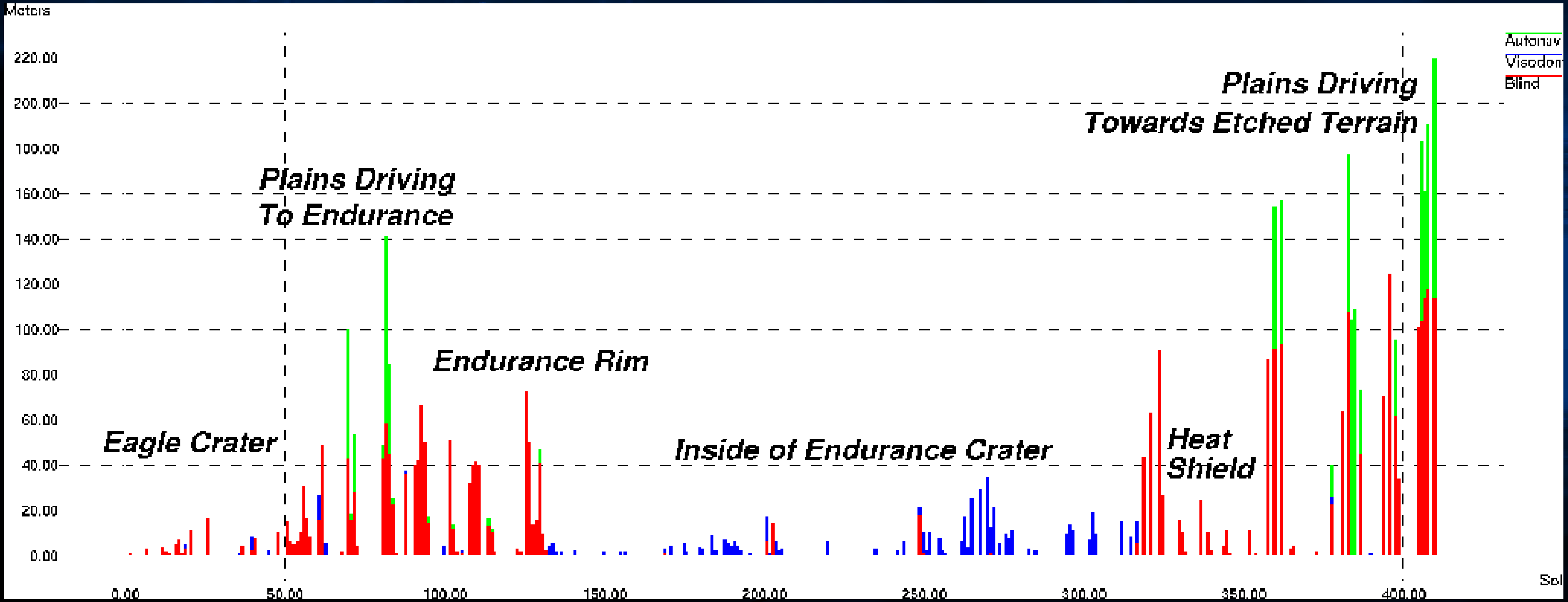
Opportunity Drives through Sol 410

NASA/JPL/MSSS

Driving Modes:
Blind
Autonav
Visodom

NASA/JPL-Caltech

Opportunity Drive Modes through Sol 410



Data from rover's onboard position estimate

NASA/JPL-Caltech

MER Autonomy Growth

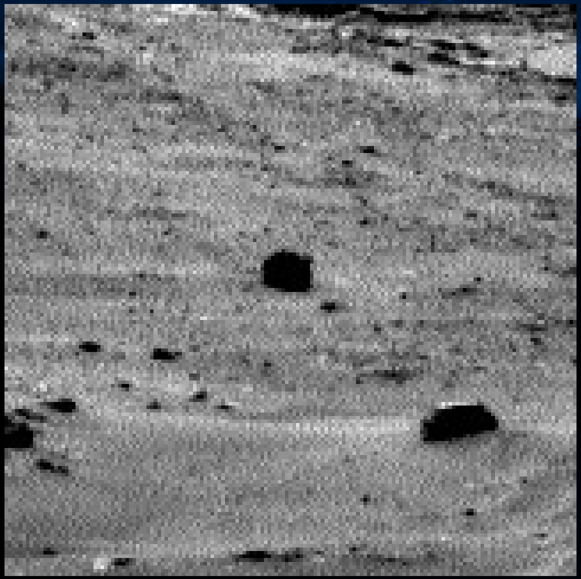
2000
- Dense Stereo Vision
- Autonomous Terrain Assessment
- AutoNav

2003 Additional pre-landing capabilities
- Visual Odometry, Slip Checks
- Guarded Driving
- Find a Rock / Turn to a Rock

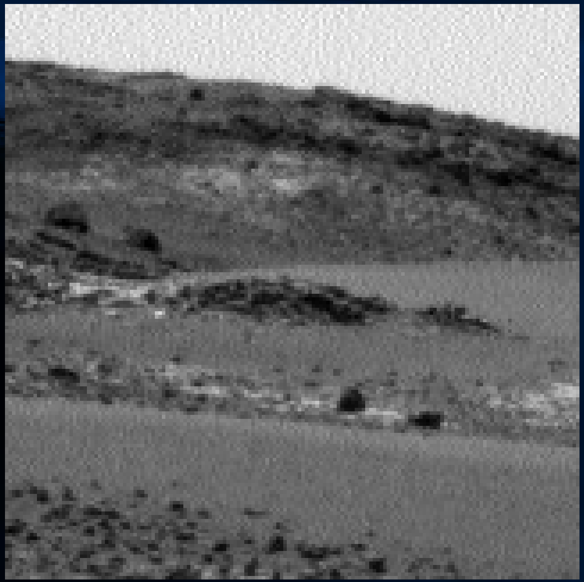
2004 Landing!

2006 FSW R9.2 New Technologies
- Visual Terrain Tracking
- AEGIS
- IDD Auto-Place
- D* Planner

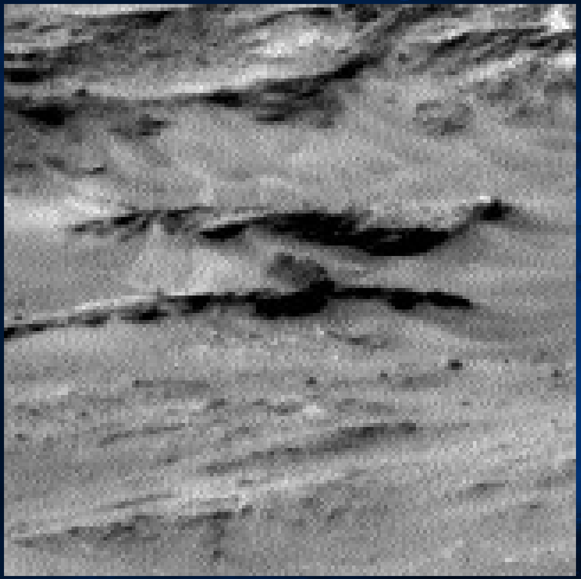
Curiosity Visual Target Tracking



Sol 743



Sol 923



Sol 967

NASA/JPL-Caltech

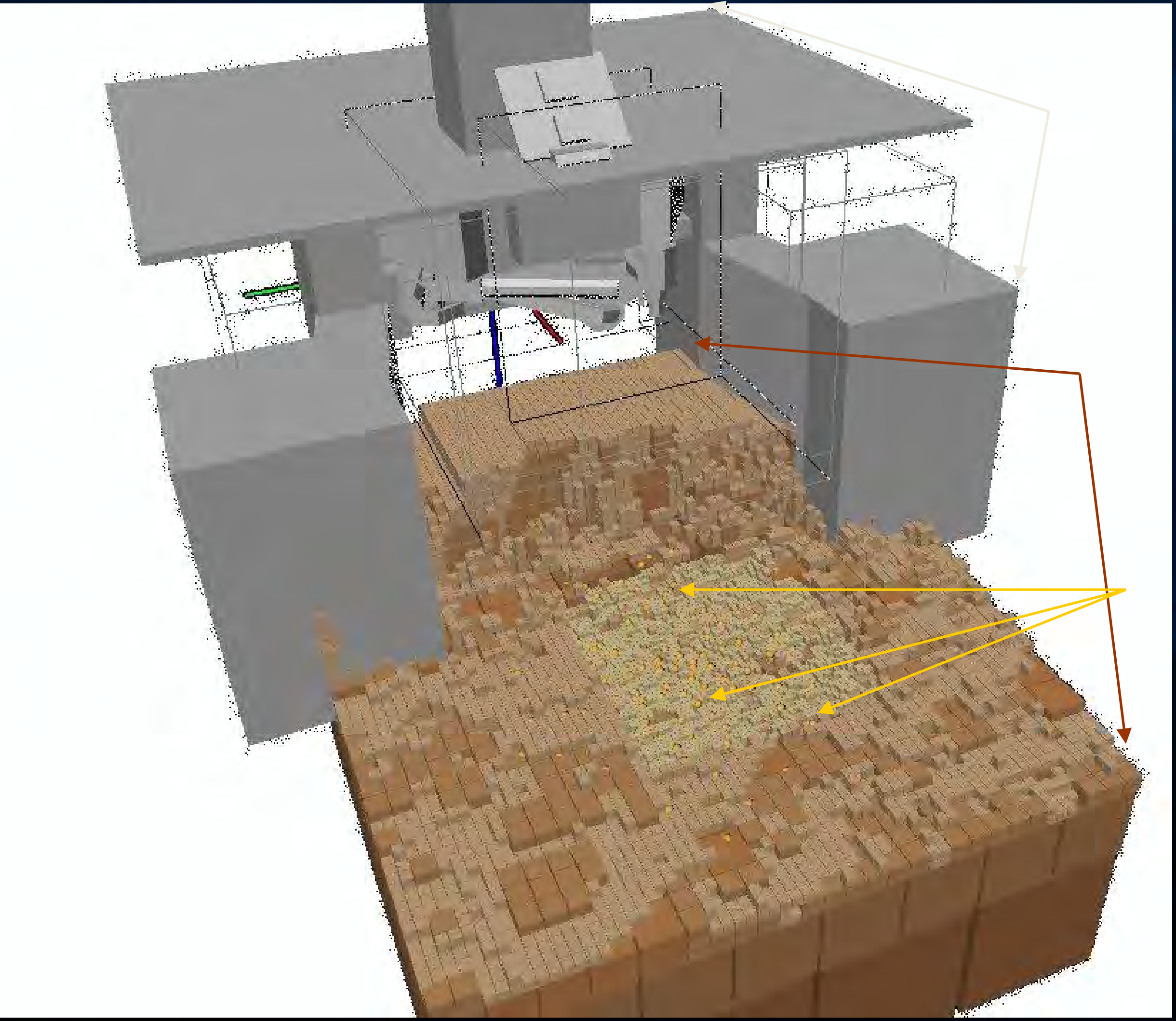
Autonomous Science: AEGIS

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

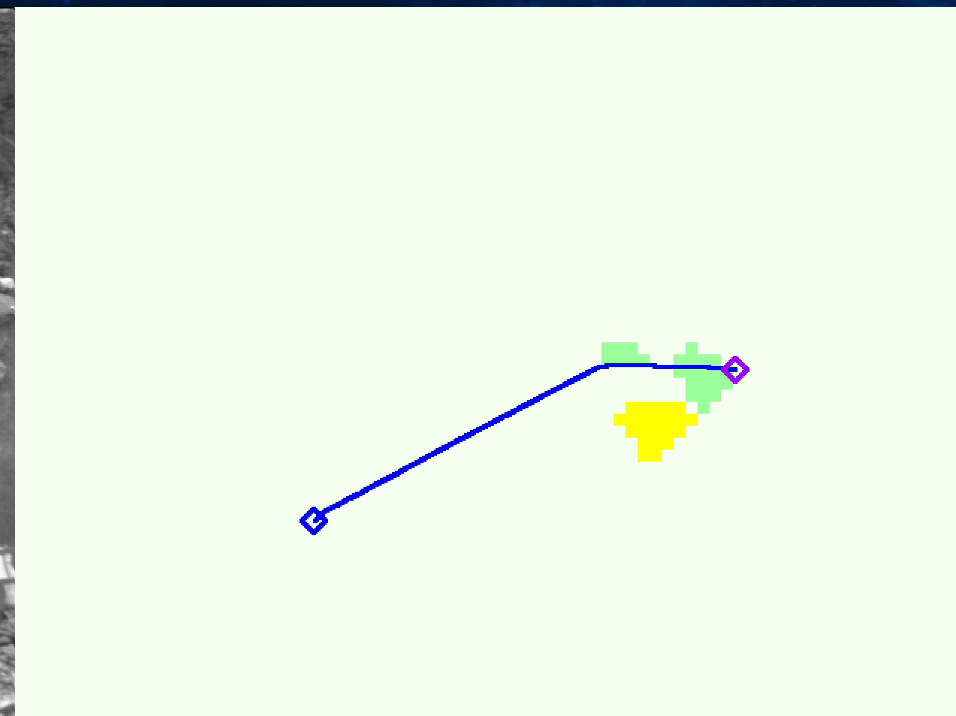
Rover Exclusion Zones

High resolution terrain model processed onboard

Potential IDD Placement targets

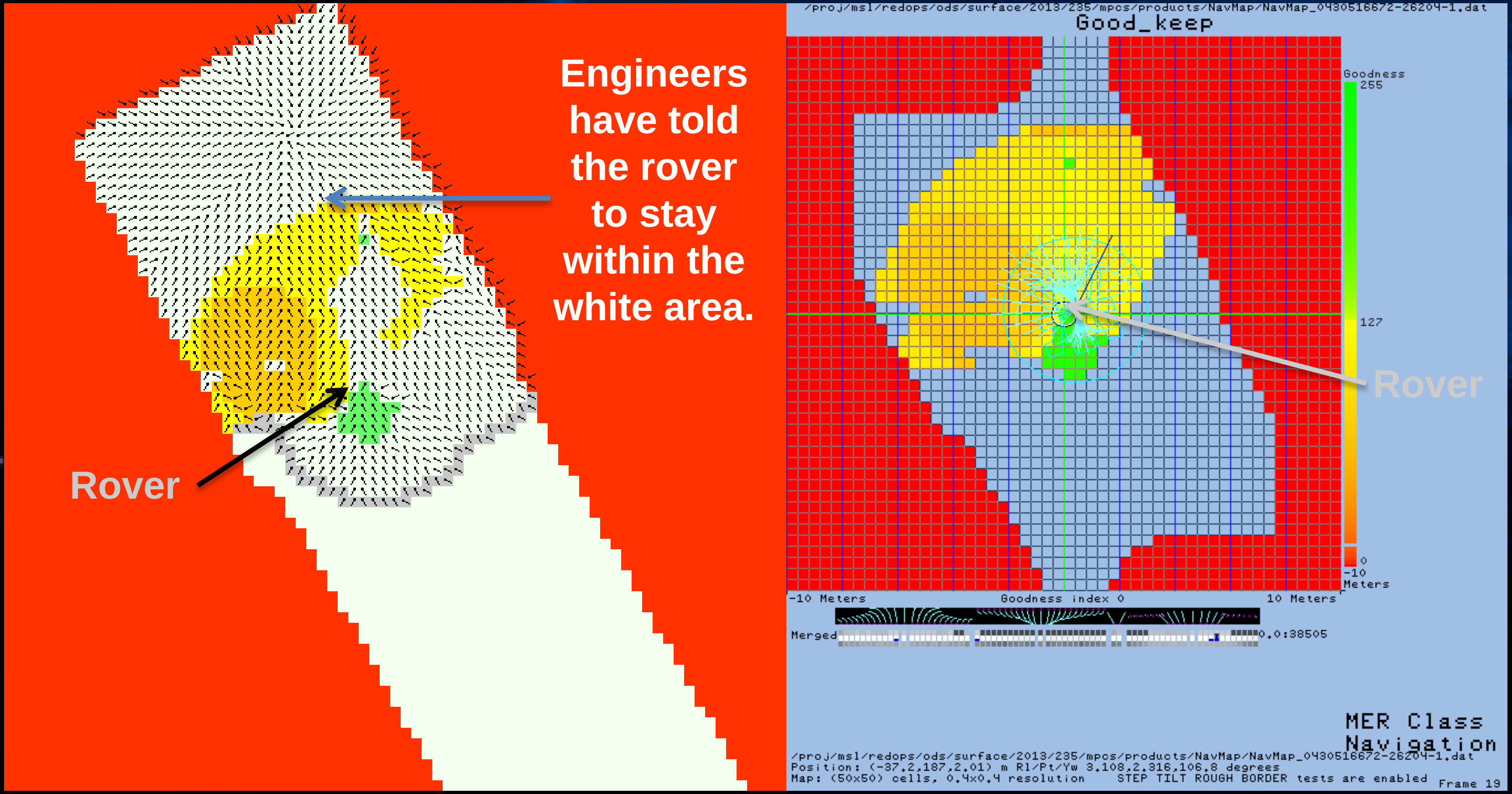
D* Global Planner in the lab

Overhead Imagery



Field D* Cost Map NASA/JPL-Caltech

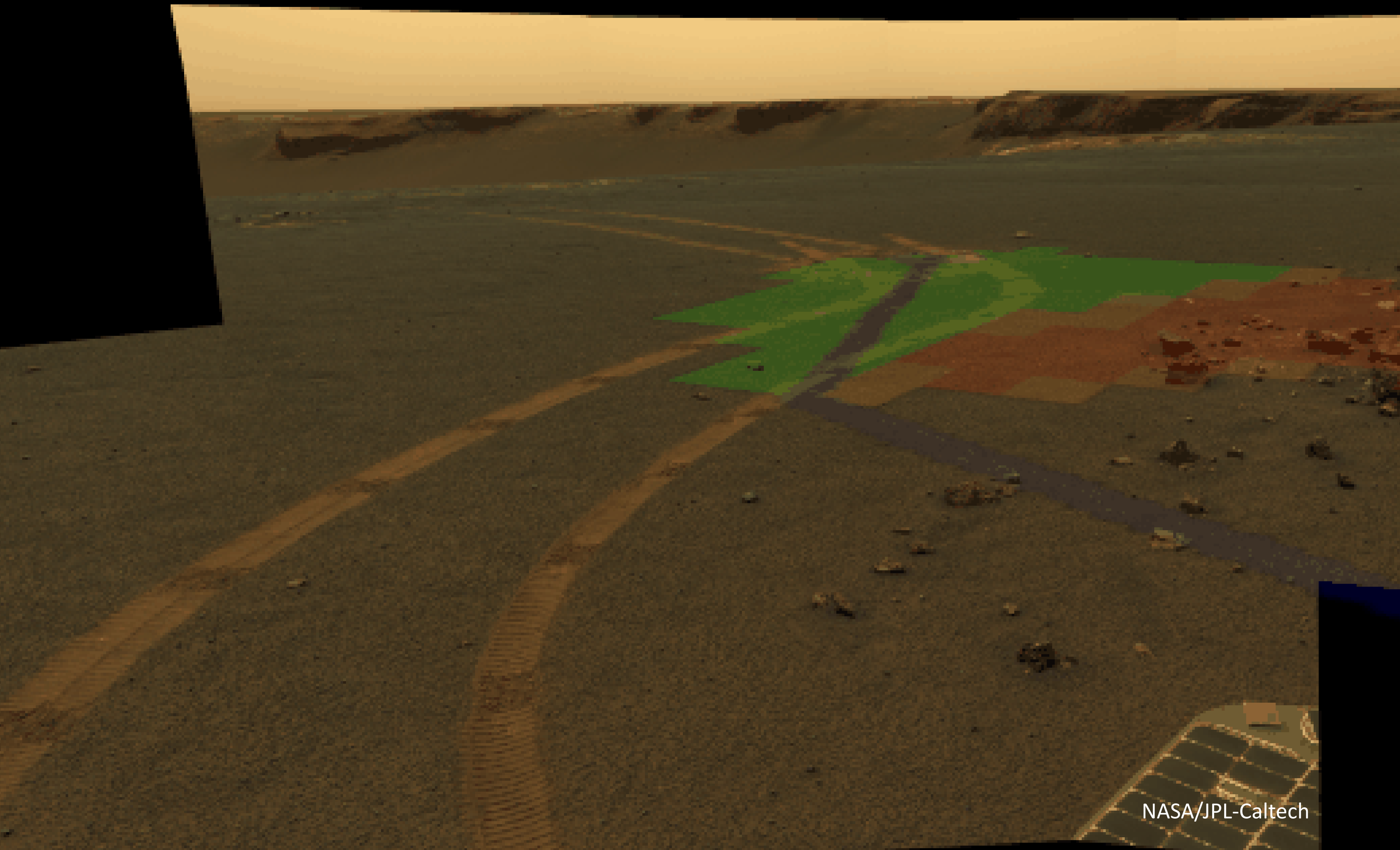
D* maps on Mars



NASA/JPL-Caltech

Yellow means drive carefully, just like on Earth.

D* Global Planner on Opportunity



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
…

Autonav Throughput Bottlenecks

Sensing

- Sojourner: Stereo Range (only 20 points)
- MER: Image Load (20 seconds to grab, transfer, log)
- MSL: Stereo Range (Hazcams), Mast Slewing
- MSL: Image Load (7 seconds to grab, transfer, log)
- M2020: Image Load (9 seconds to transfer to FPGA)

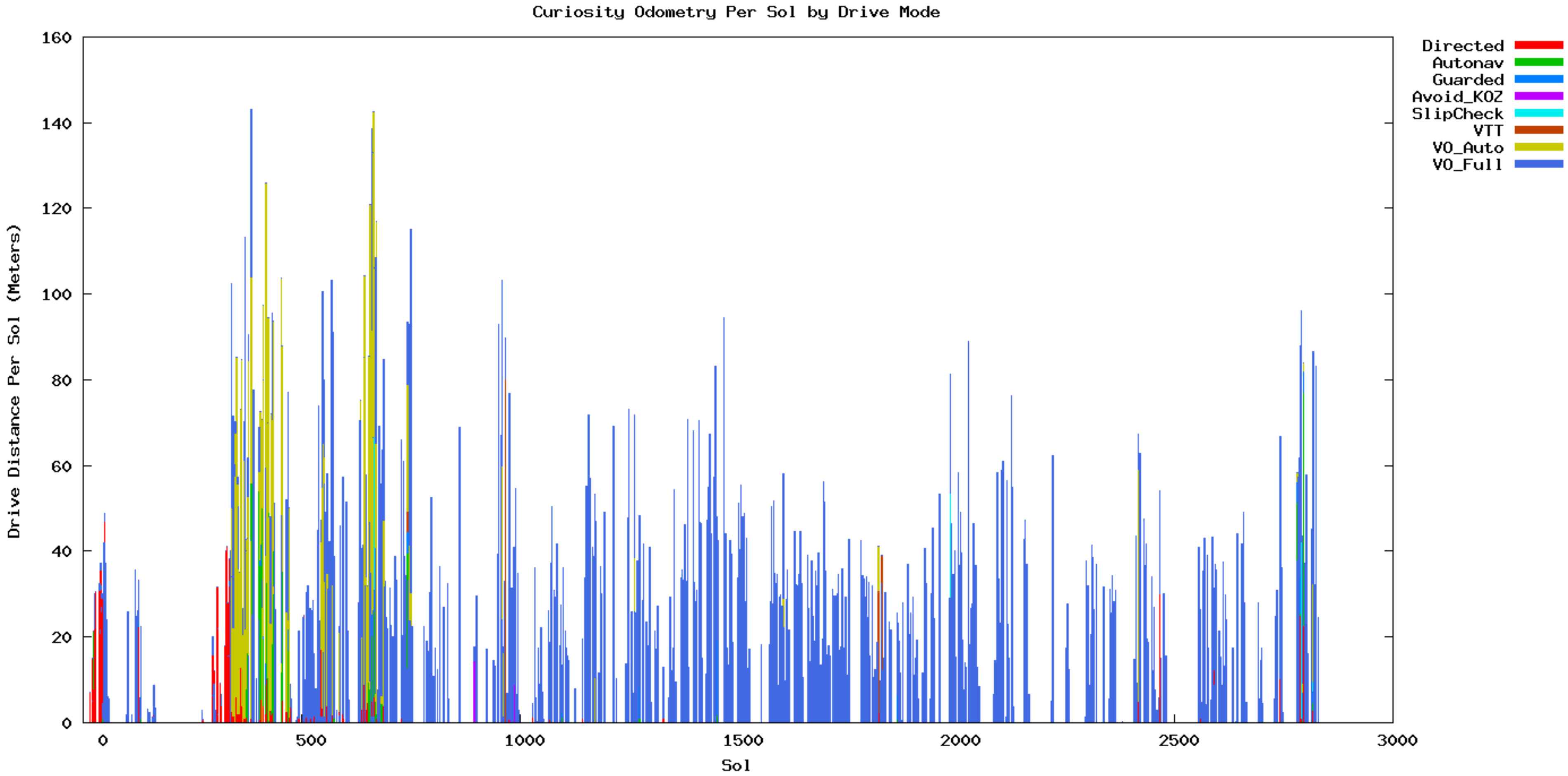
Computing

- Sojourner/MER/MSL: 2, 20, 133 MHz (> 1 minute/step)

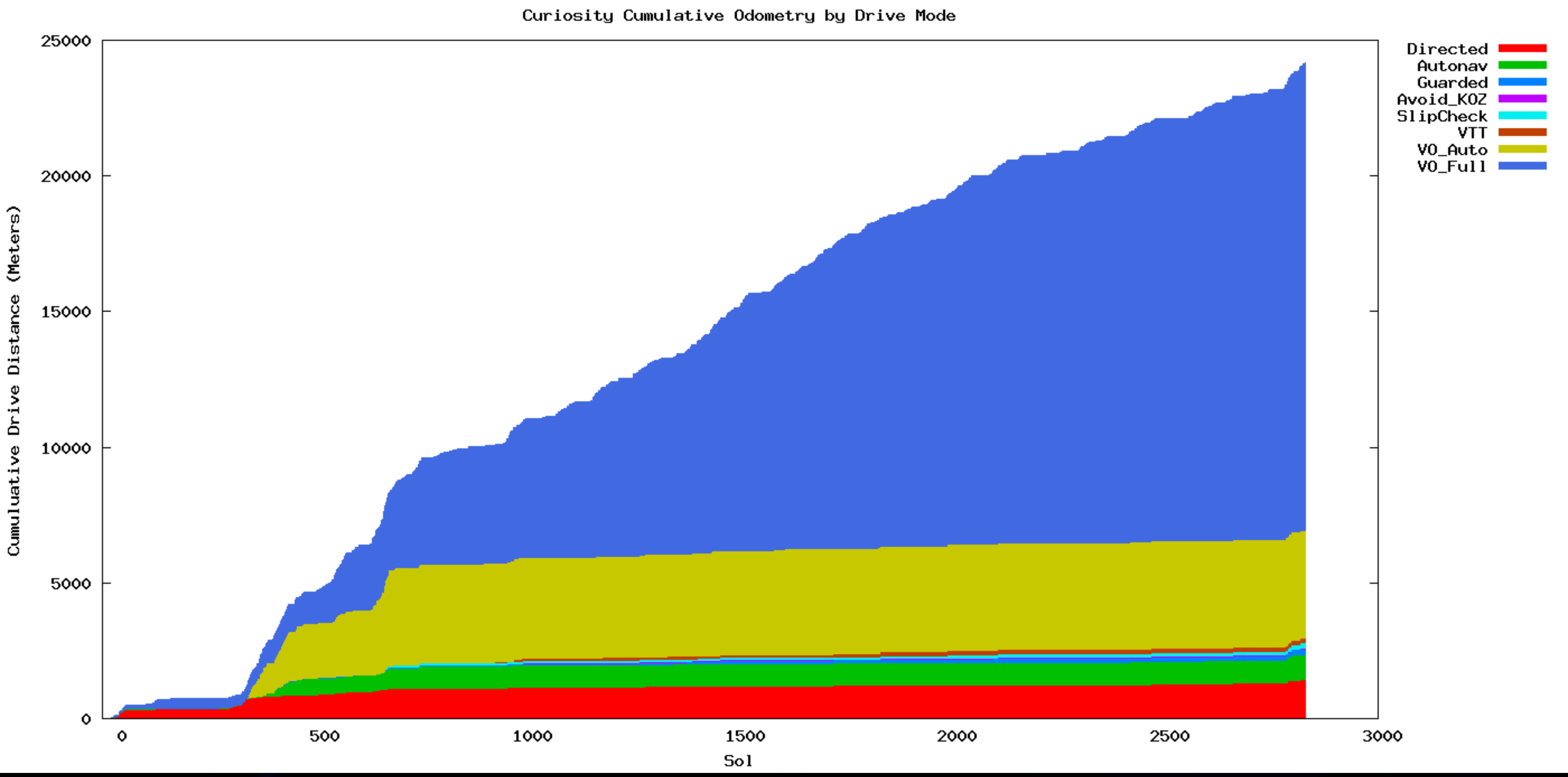
Drive Speed:

Rover	Realtime Drive Rate	Distance Driven/hour	Autonav Distance/hour	VO Distance/hour
Sojourner	0.6 cm/s	< 21 m	?	N/A
MER/MSL	4.2 cm/s	100 - 151 m	10 – 25 m	~30 m / ~40 m [~60m]
M2020	4.4 cm/s	107 - 159 m	75 – >100 m (estimated)	>100 m (estimated)

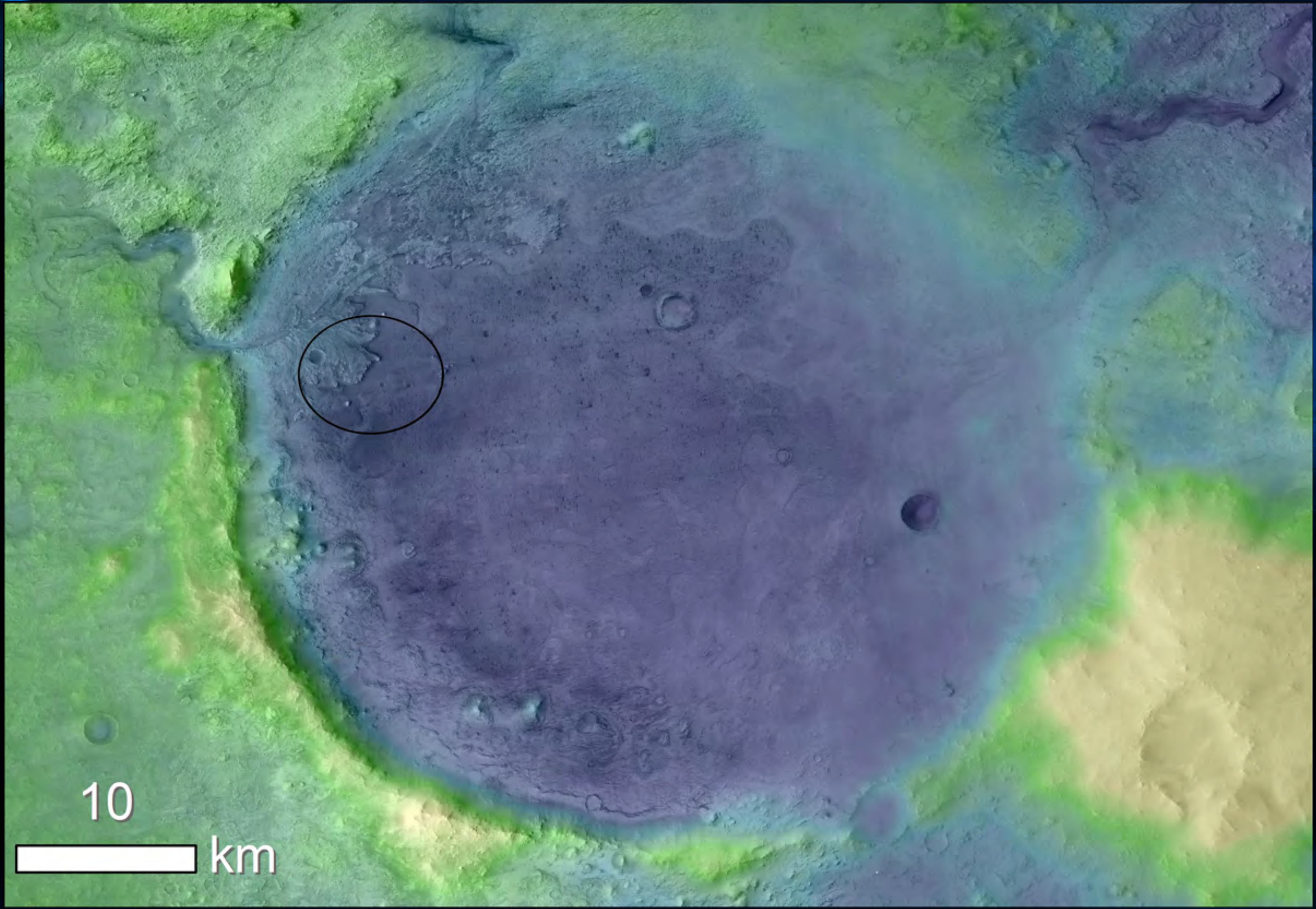
Curiosity Daily Drive Stats



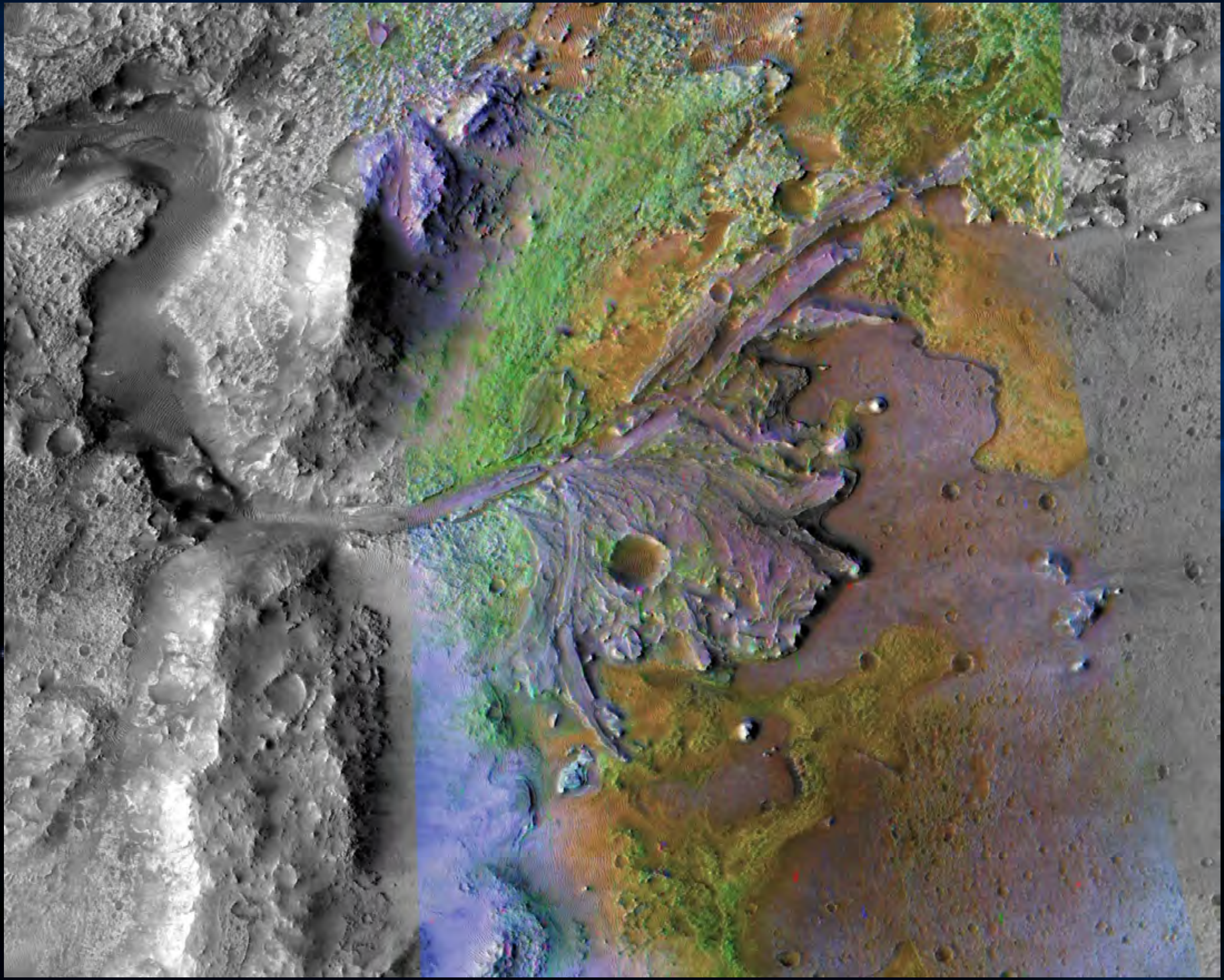
Curiosity Cumulative Drive Stats



Perseverance Landing Site: Jezero

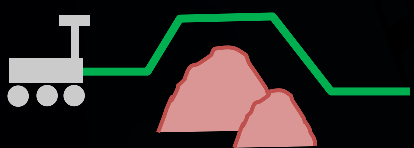


Jezero Motivated Improved Autonav



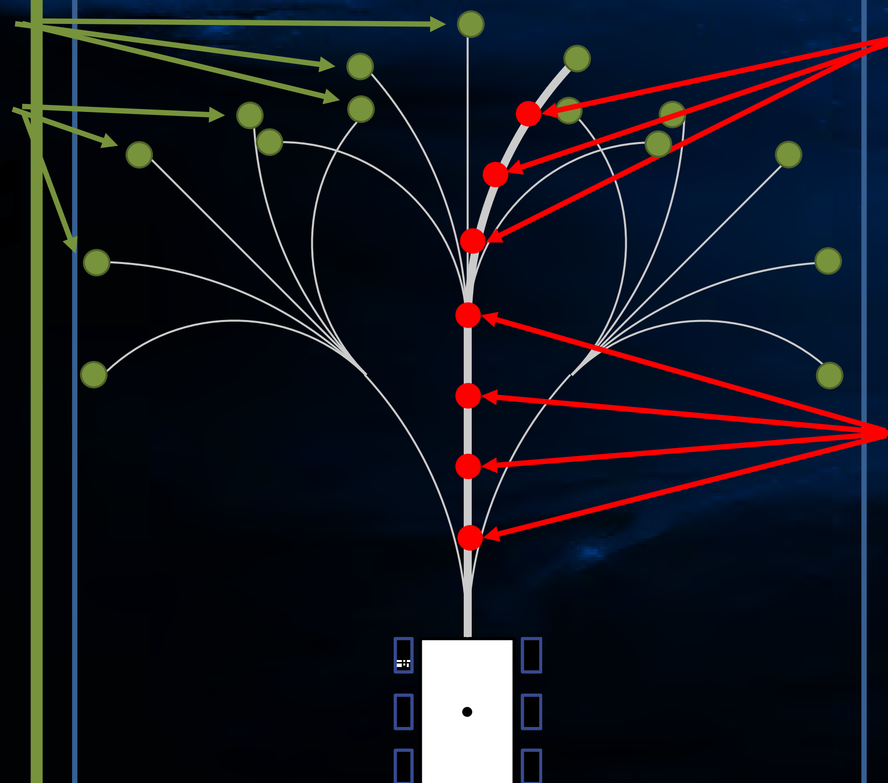
M2020 AutoNav Approach`

Global Planner



- Gives cost from the end of tree to goal
- Routes computed on 200m x 200m map
- 1 m resolution
- Considers slope, roughness, keep-out zones

Local Planner



- Selects best path for the next 6m

ACE

(Approx. Clearance Est.)

- Runs every 25cm
- Checks clearance, tilt, suspension and attitude limits, wheel drop

Courtesy Olivier Toupet

Lessons Learned

Autonomy increases Mission Safety and Capability
- Autonav enables exploring unseen terrains safely
- VO was an “extra bonus”, now a critical safety component on MSL and M2020

Prepare for the Unexpected
- Must adapt to new terrains
- Ability to run tests in simulation, on EM, patch FSW quickly, and update FSW over long term is critical

Keep it tunable
- Typical FSW guidance is to reduce conditionals and parameters, but for Autonomy adaptability is key.

Perseverance Awaits!

Please Post Questions in Q&A

Backup

Athena Rover (Sample Return) 1999

GESTALT Autonav: Summer 2000

July 2000 MER Autonomy Proposal

Extra Credit: Additional Features for more Autonomy

Some additional capabilities that are being explored:

- **Global Adaptive Path Planning**
  - **D* planner uses A* (optimal) search, allows for missing or corrected data, *and* handles cul-de-sacs**
  - **Has been demonstrated on UGV and Bullwinkle, now being ported onto Rocky 7, TMR**
- **Visual Servoing for targets > 2m away**
  - **Use image template matching and approximate pose estimates to continuously track a target while safely driving toward it.**
  - **This capability has been demonstrated on several research tasks: TMR, Marsokhod**
- **Range Servoing for targets < 2m away**
  - **Servo on the shape of a target rather than its appearance, since the latter changes dramatically on final approach**
  - **Demonstrated to track small surface rocks with spectral filter on Rocky 7**
- **Visual Odometry for improved position estimation**
  - **Automatically track dozens of features (using both appearance and range) to more precisely estimate vehicle motion**
  - **Fragile to uncompensated tilt, but demonstrated on data collected from Rocky 7 and other rovers.**
- **Overlaying of dense range maps for improved position esimation**
  - **Perform robust matching use the dense surface mesh around the vehicle**
  - **Demonstrated on Rocky 7, FIDO**

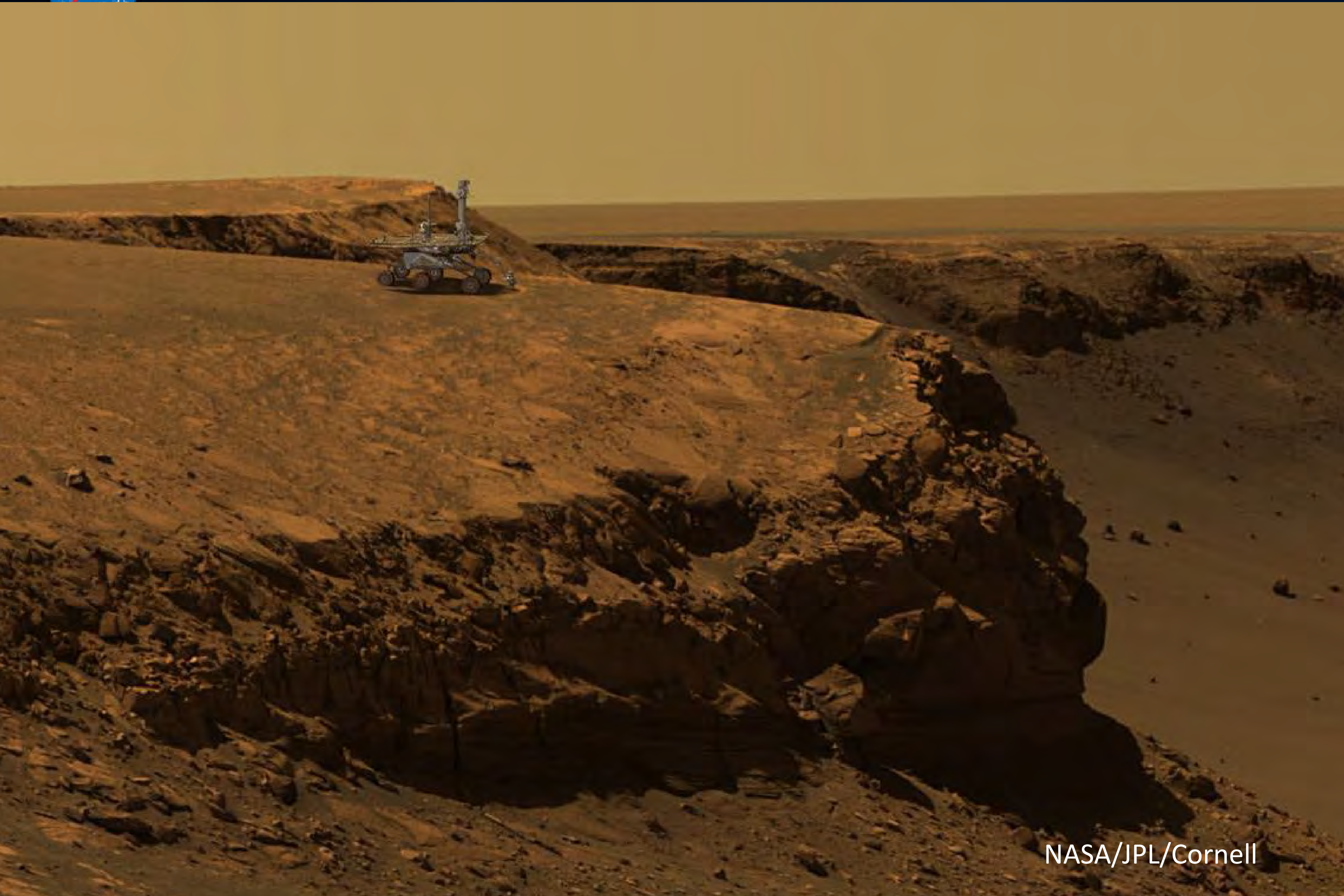
July 2000 MER Autonomy Proposal

Extra Credit: Ad... more Autonomy

Some additional capabilities that are ...

- Global Adaptive Path Pla...
  - D* planner uses ... missing or corrected data, an... ...cs
  - Has been demon... ...ow being ported onto Rocky ...
- Visual Servoing for ... ...ay
  - Use image te... ...g and appr... ...s to continuously track ... ...fely driving toward it.
  - This capabili... ...nonstrated on ... ...: TMR, Marsokhod
- Range Servoing f... ...away
  - Servo on the ... ...t rather than its appeara... ...anges dr... ...nal approach
  - Demonstrated ... ...urface rocks with spectral ...
- Visual Odometry for ... ...n estimation
  - Automatically tra... ...s (using both appearance and ... ...imate vehicle motion
  - Fragile to uncompe... ...trated on data collected fro... ...vers.
- Overlaying of dense range m...
  - Perform robust matching use ...
  - Demonstrated on Rocky 7, FIDO

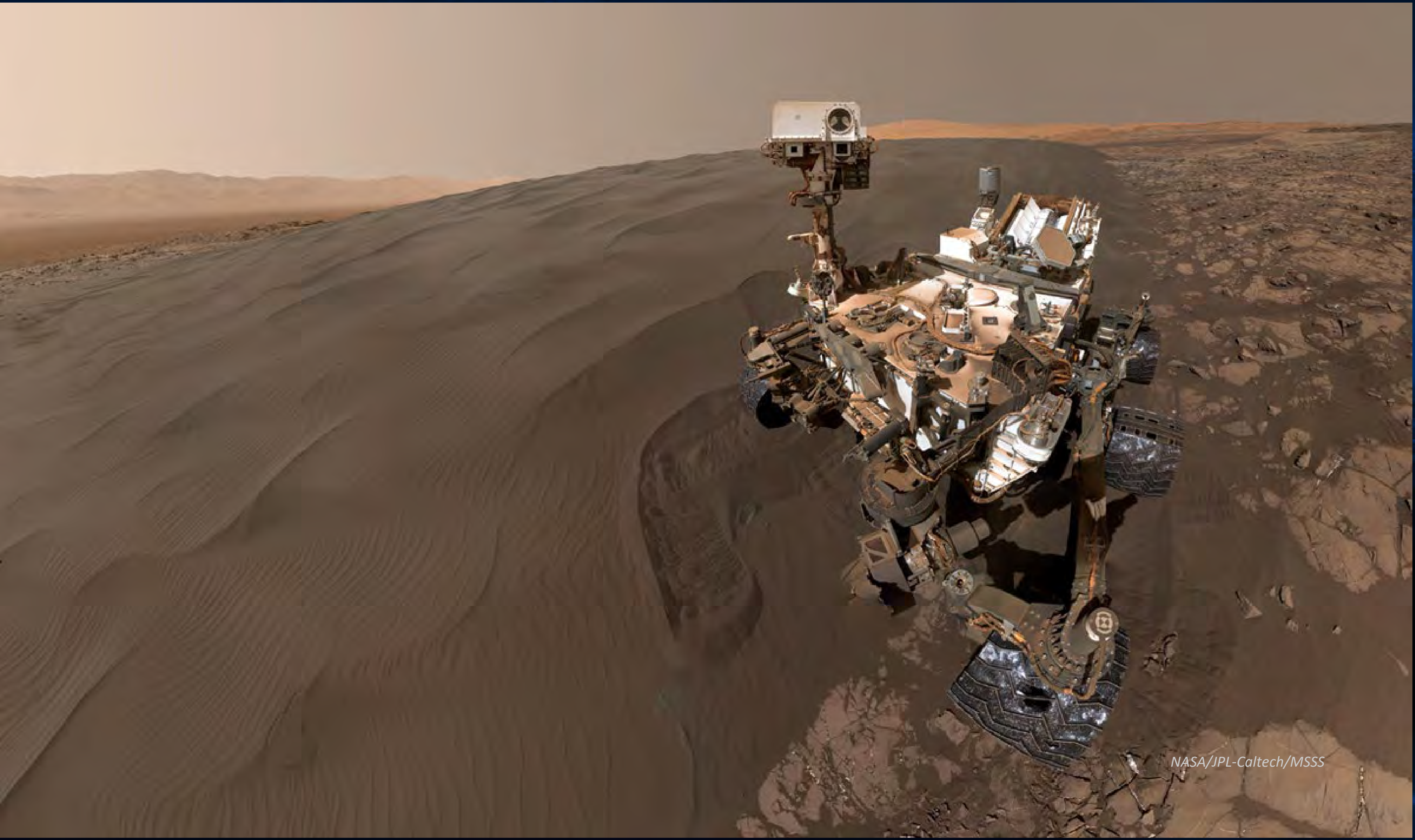
And Craters


NASA/JPL/Cornell

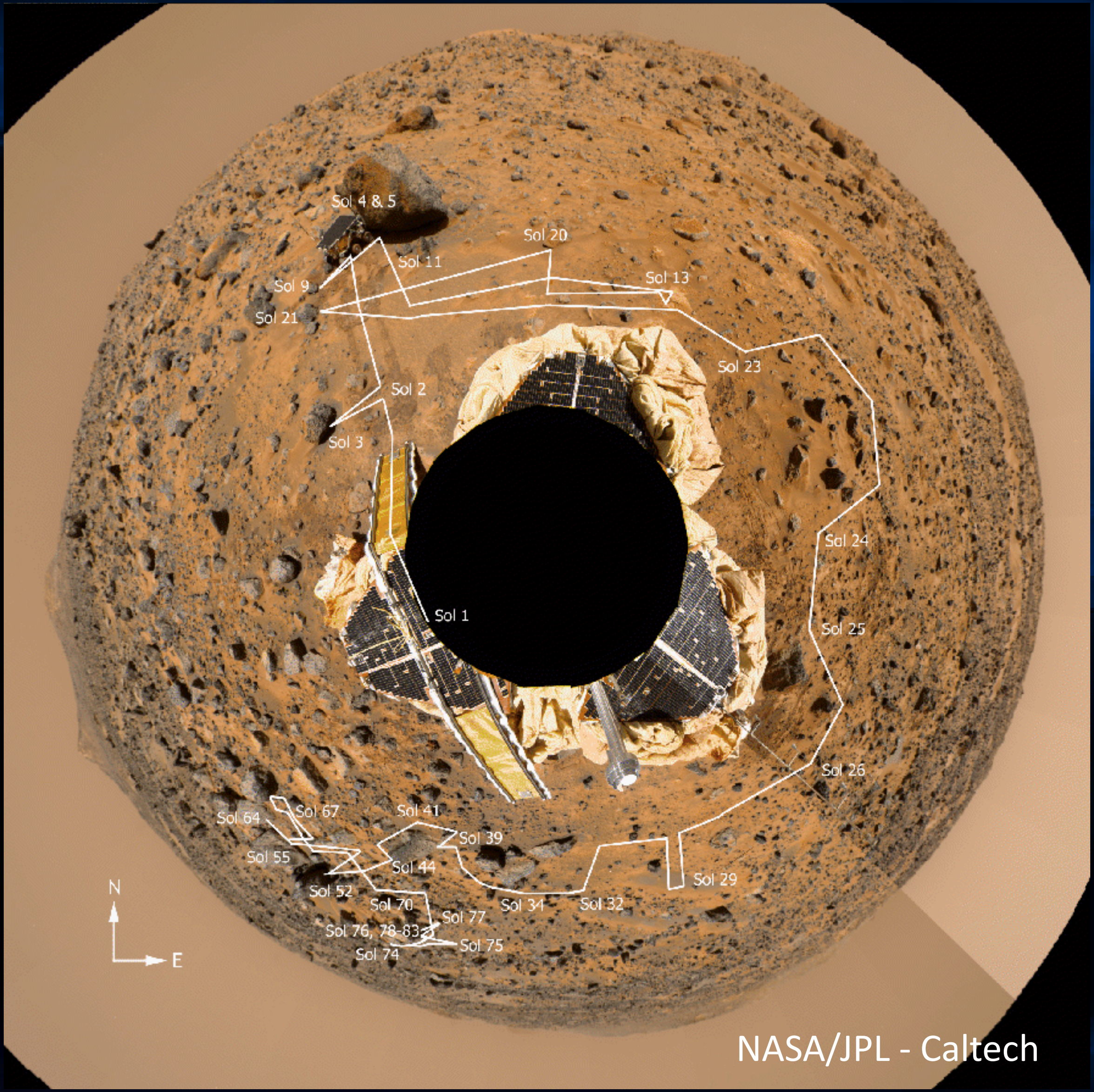
And Mountains

And Overcome Obstacles

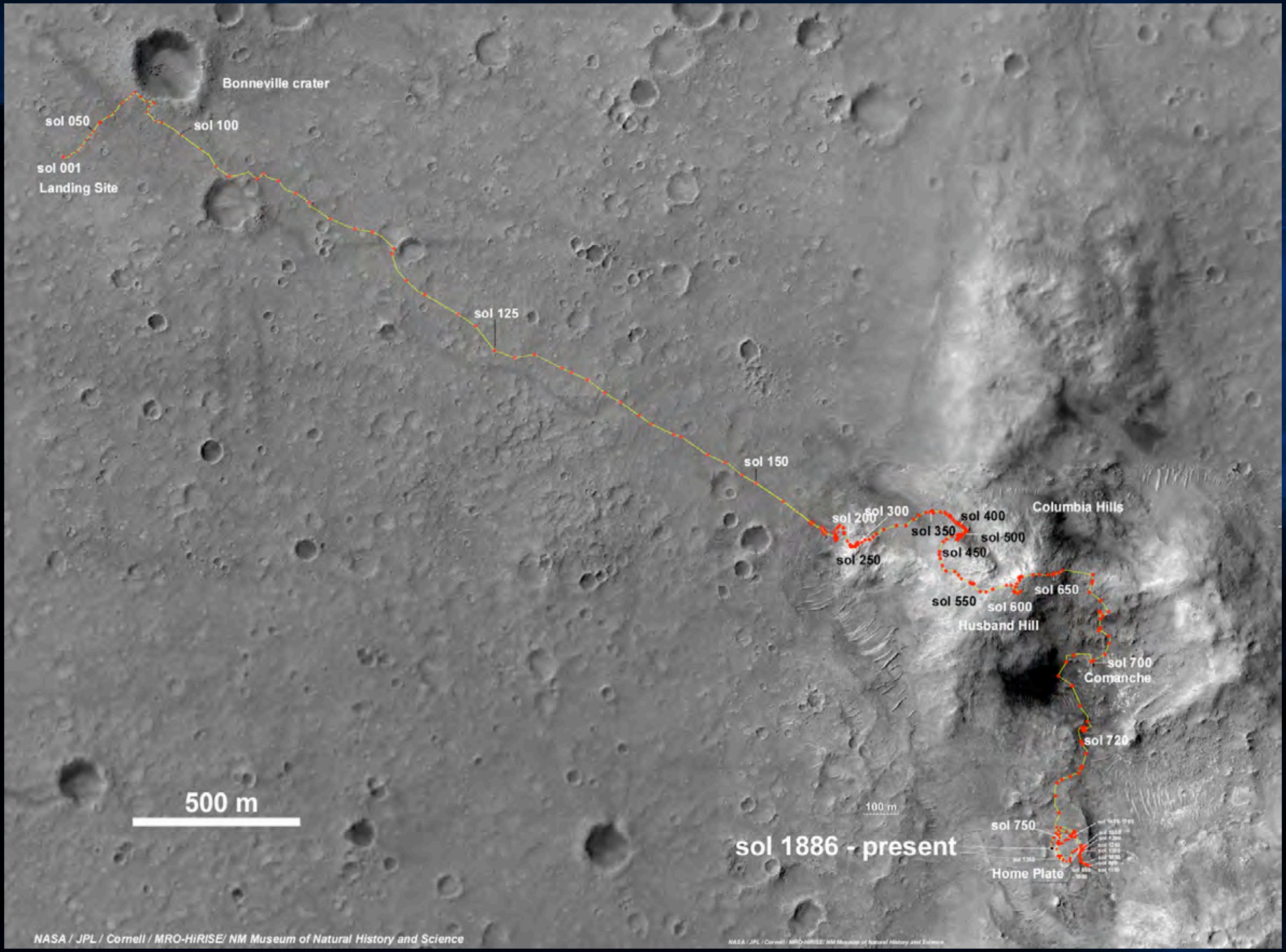
And Explore Novel Terrains



Sojourner drove 0.1 km in 0.3 years

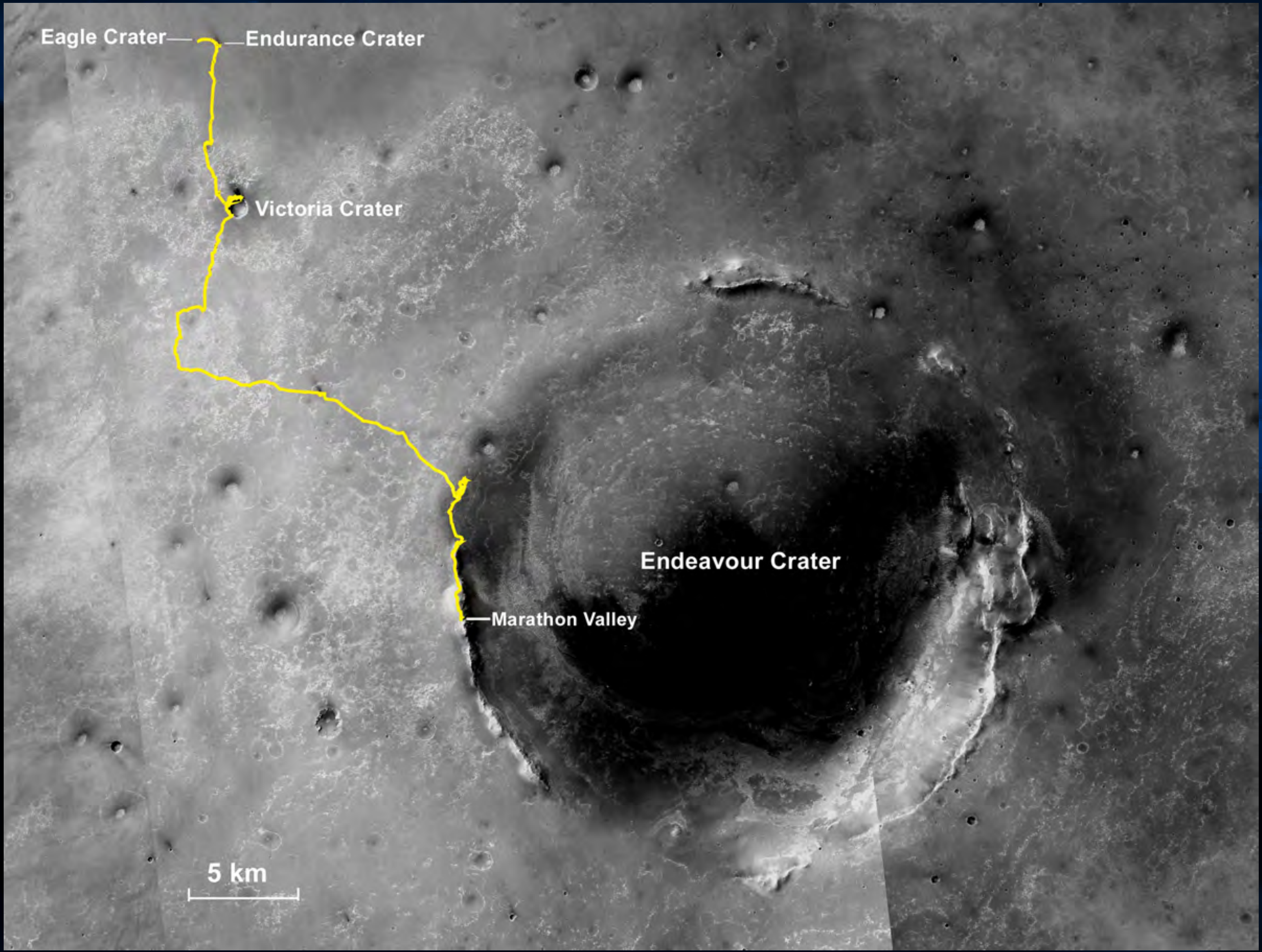


Spirit Drove 7.7 km in 6 years



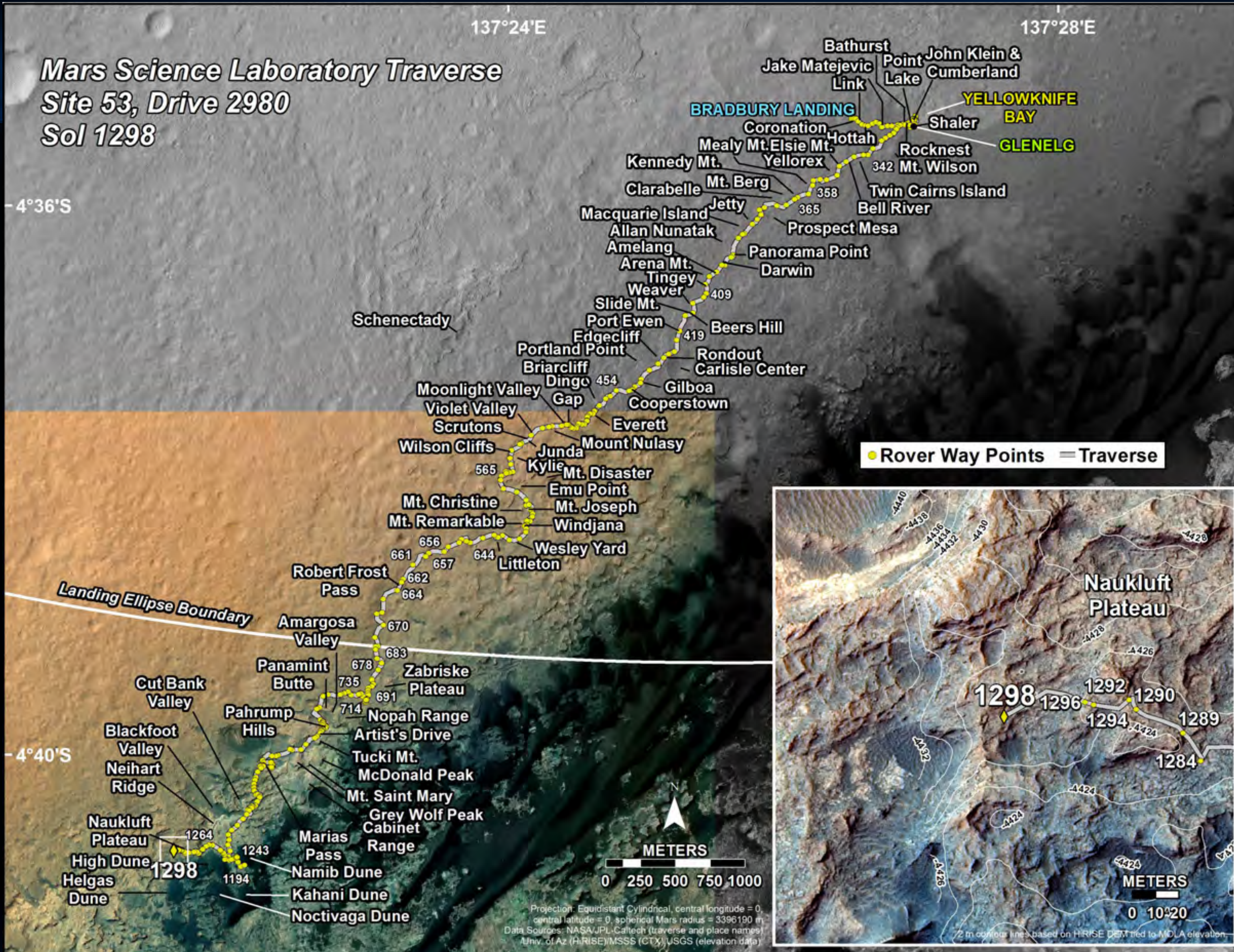
http://marsrovers.nasa.gov/mission/tm-spirit-all.html

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



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

How Did We Get Here?

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

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

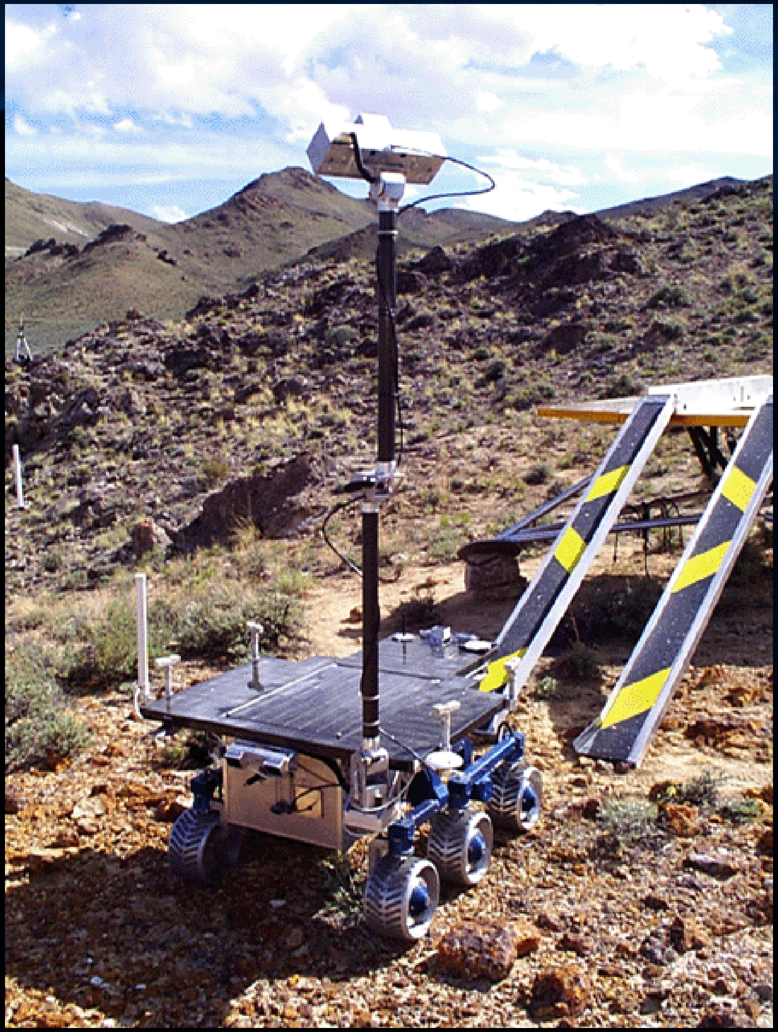
NASA/JPL-Caltech

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

Rocker-bogey suspension

Includes two manipulators: extendible mast, sampling arm

FIDO



NASA/JPL-Caltech

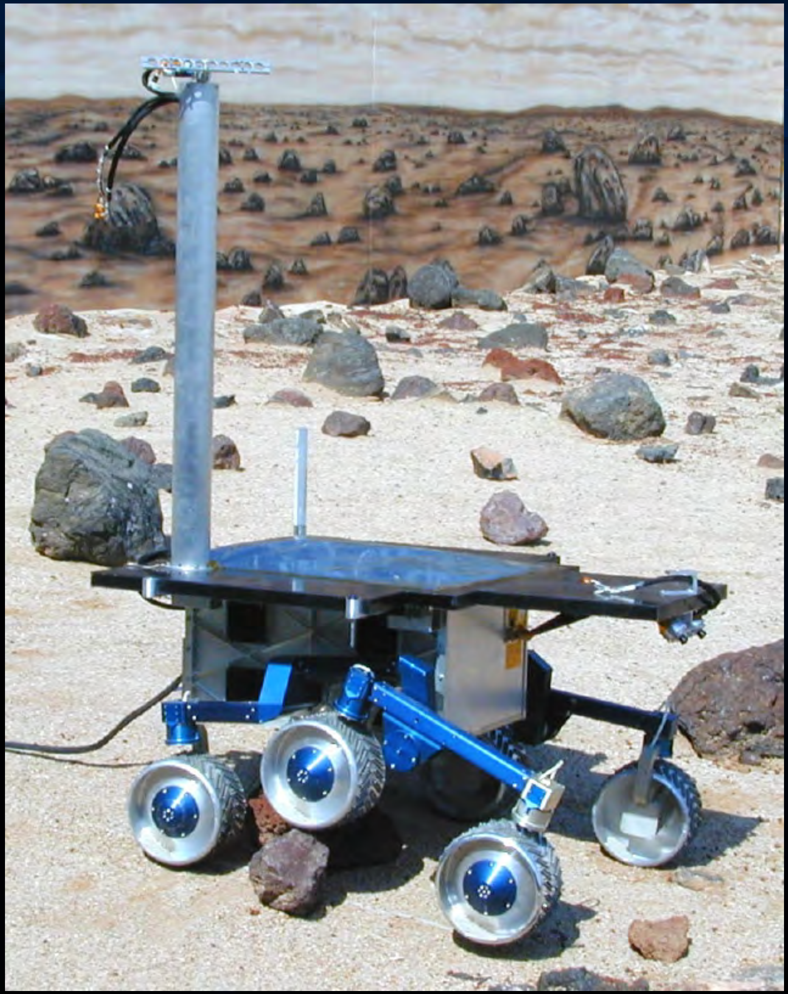
Developed by JPL (1998 – 2001+) for field training of scientists, preparing for (postponed) Mars Sample/Return mission Concept

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

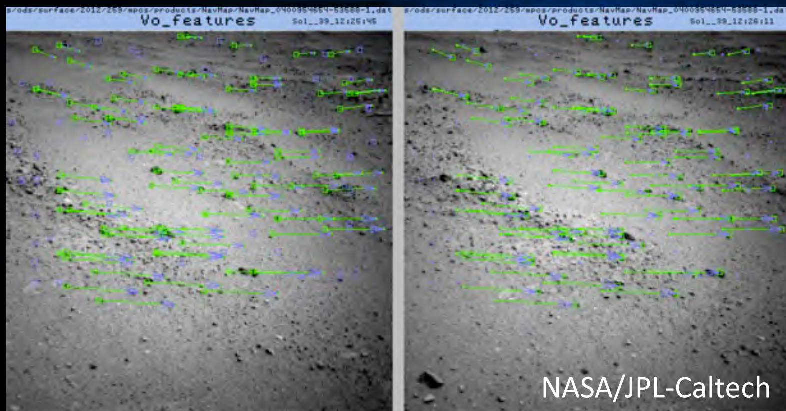
4 wheels can move about central axis, enabling rover to self-right

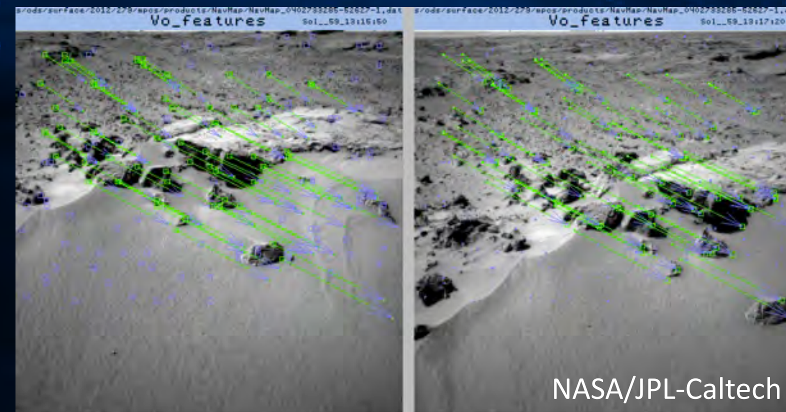
Planned launch in 2002

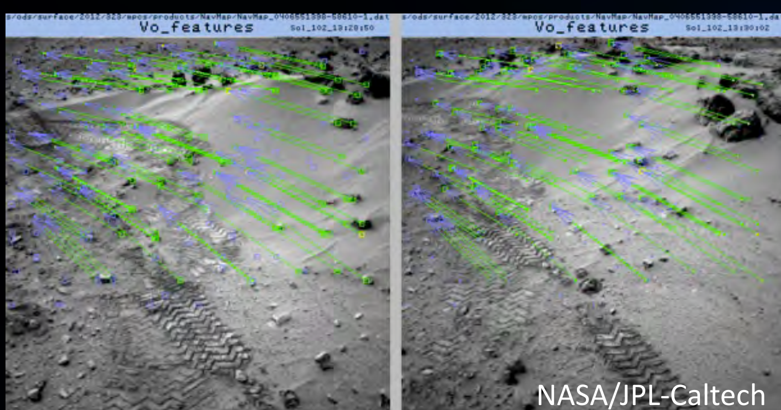
Includes spectrometer and camera for science instruments

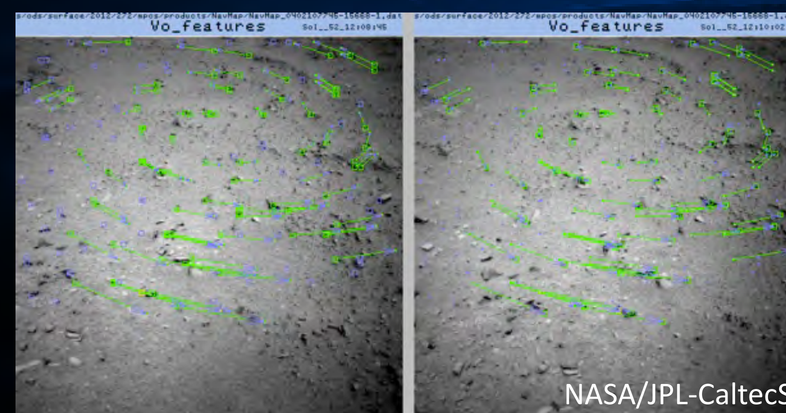
MUSES-CN rover being designed for microgravity environment

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







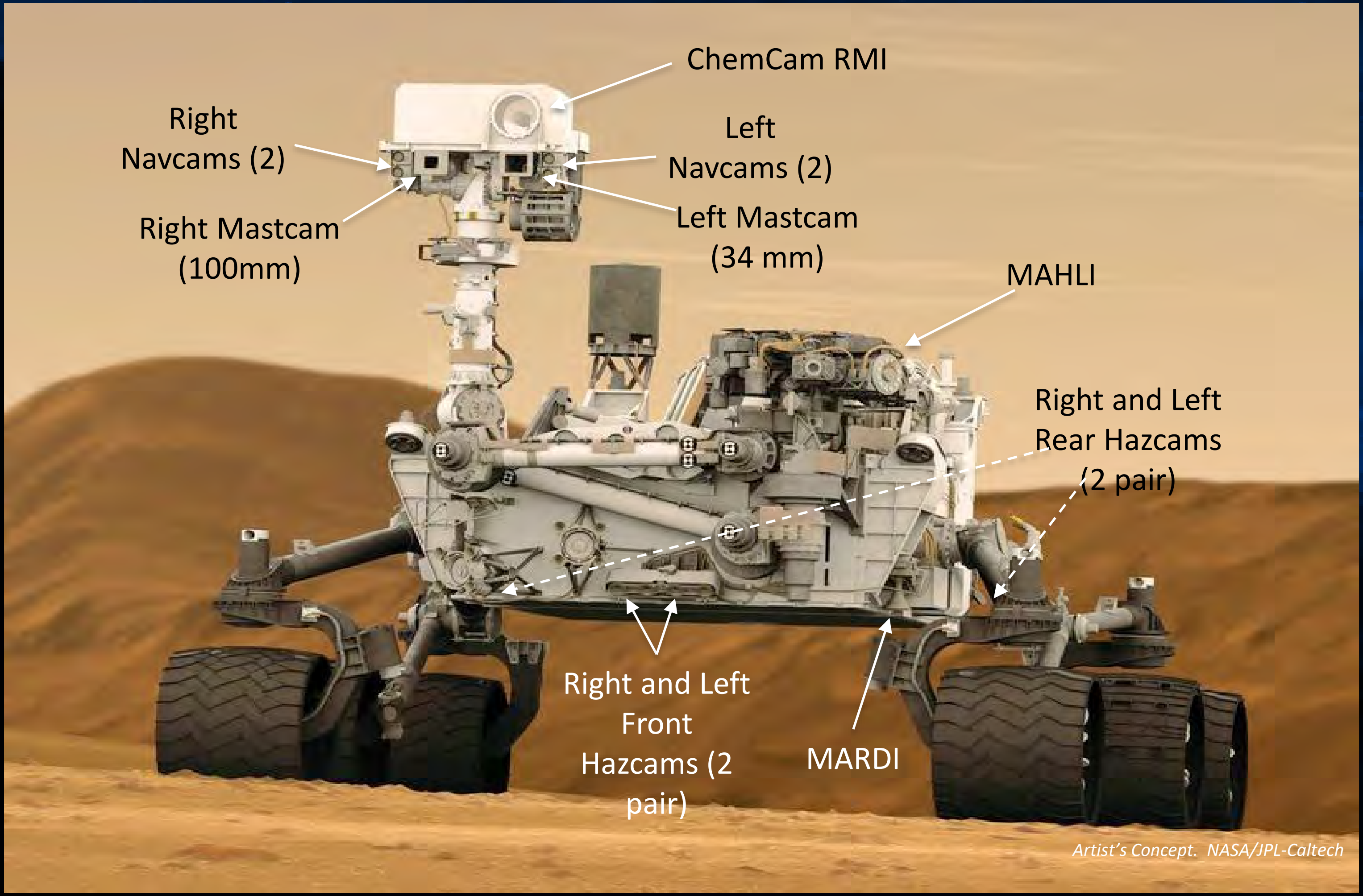


Unlike terrestrial robots, Curiosity drives as far as possible between VO images

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**

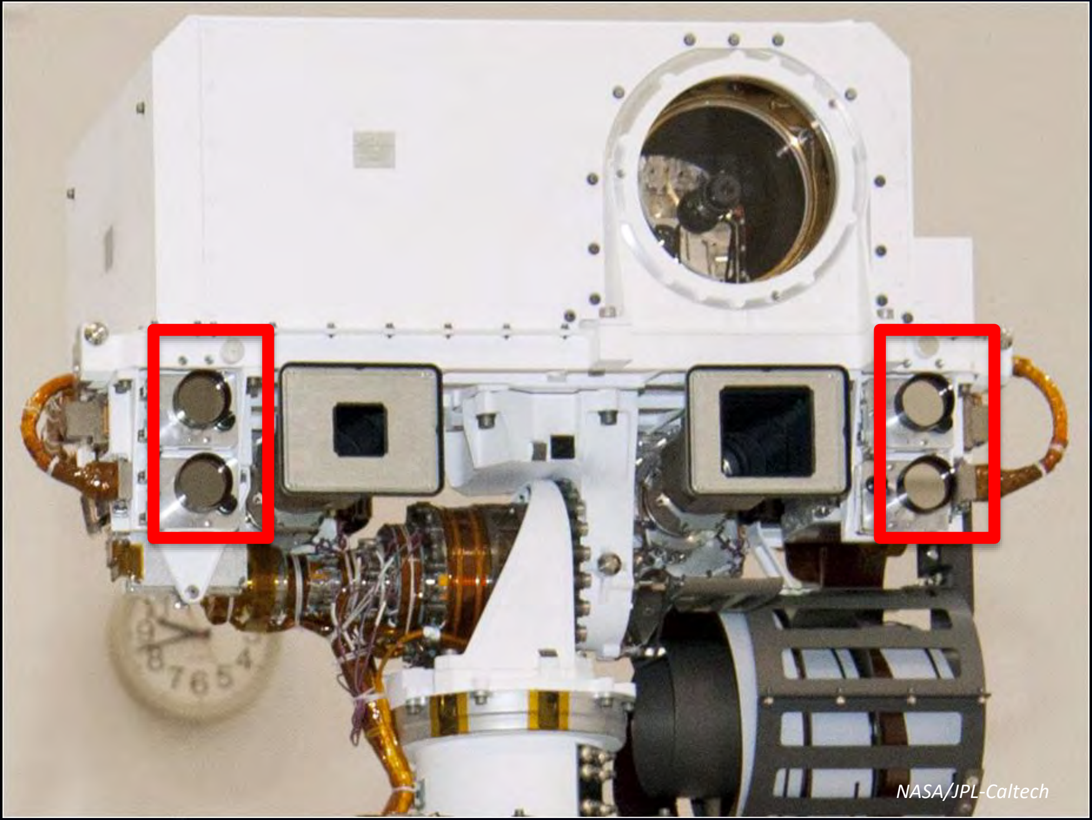
Curiosity has 17 cameras



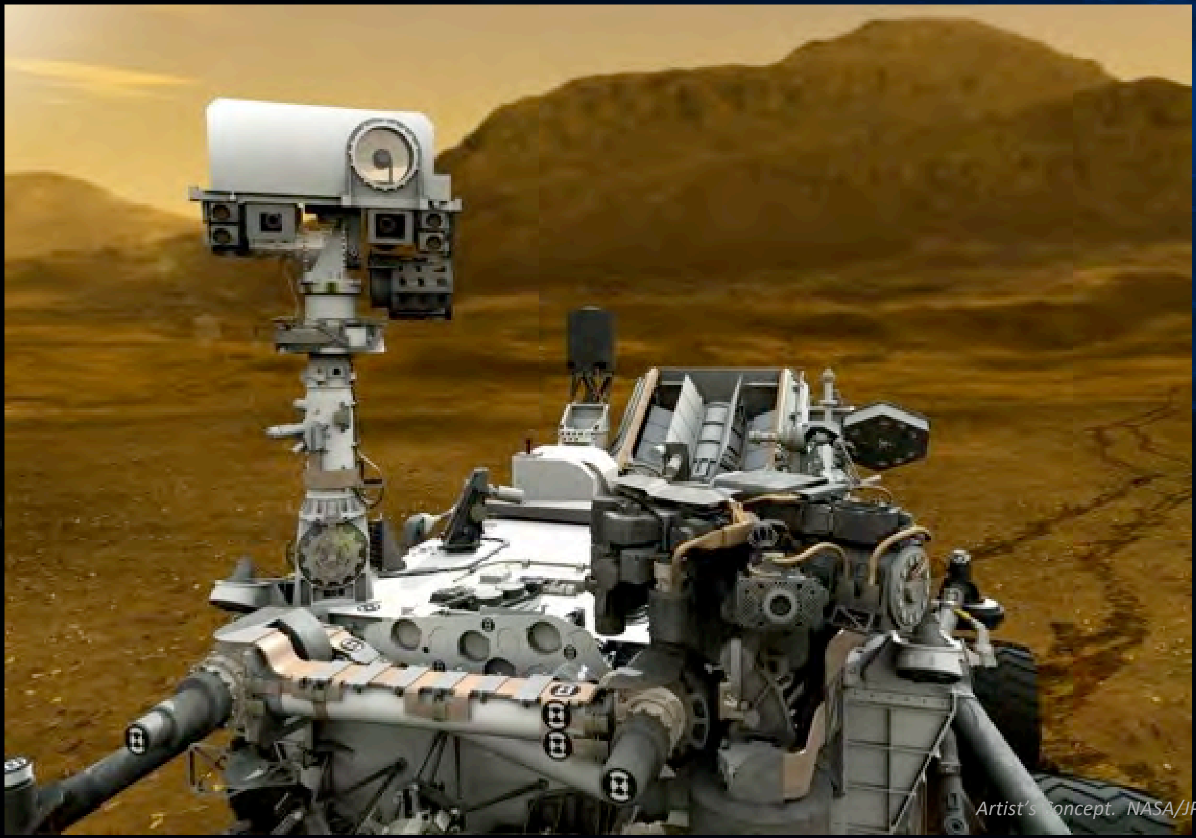
However, only the Hazcams and Navcams are tied into the auto-nav software.

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

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



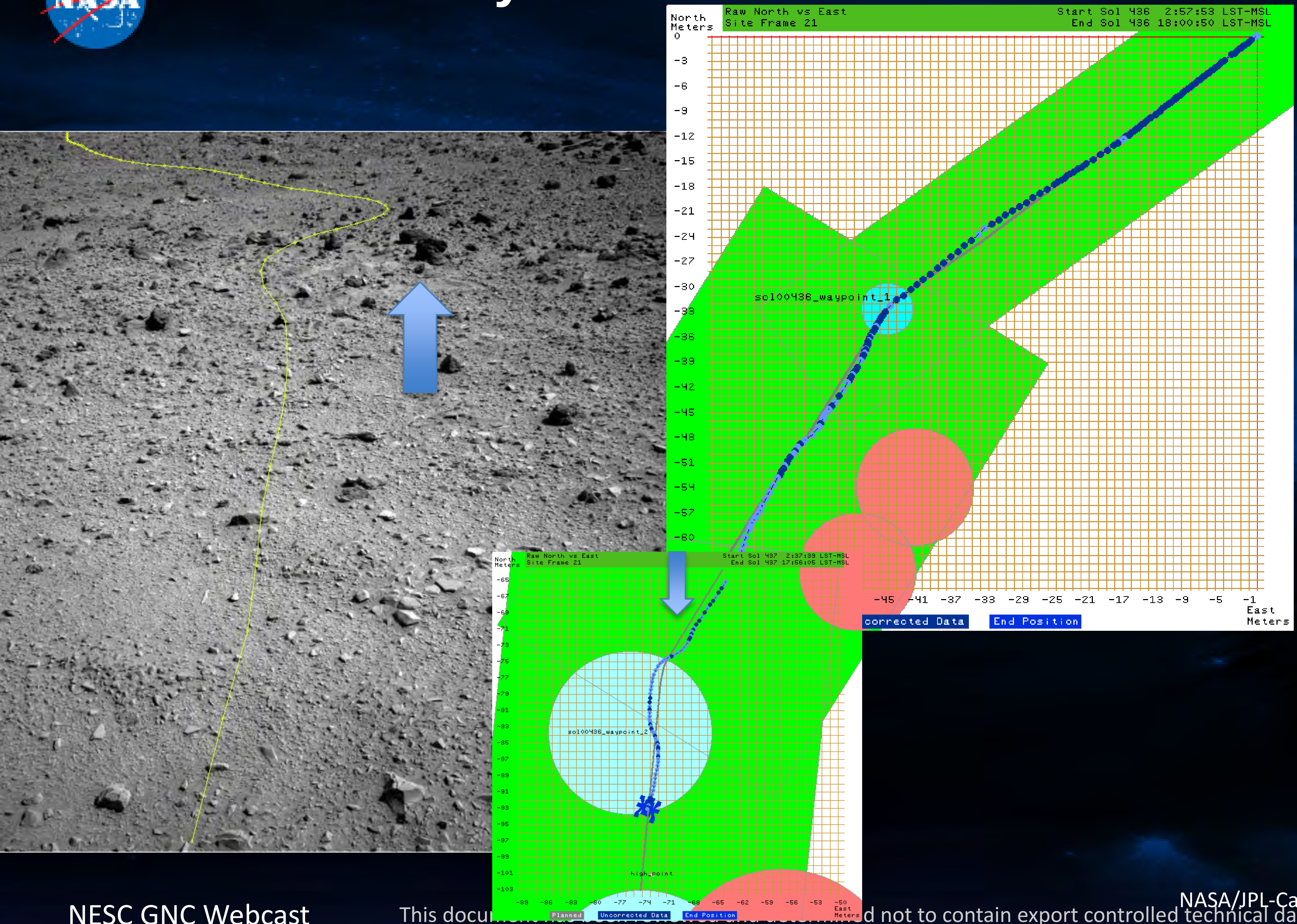
During nominal auto-nav, the rover stops every 0.5-1.5 meters, takes 4 sets of images, evaluates hazards, and then chooses where to drive.



Artist's Concept. NASA/JPL-Caltech

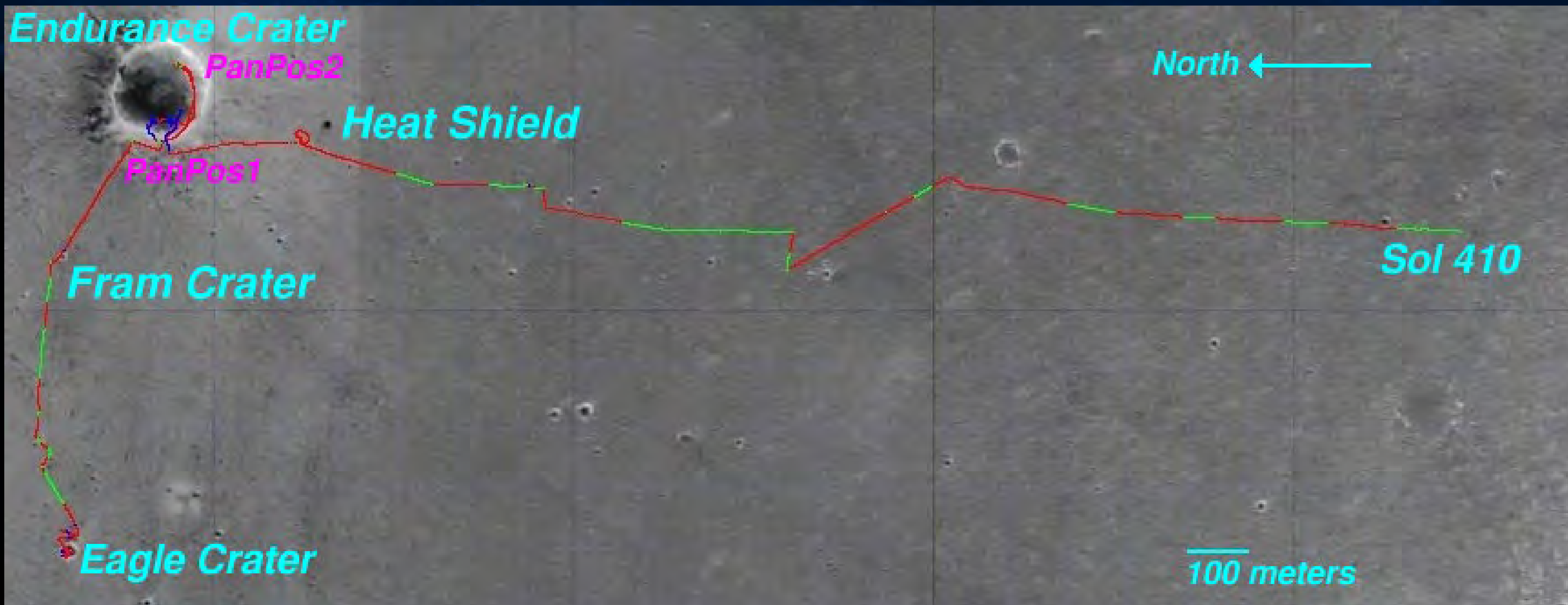
Auto-nav extends directed drives into previously unseen terrain

Curiosity Sol 436-437: Multi-sol Drive



NASA/JPL-Caltech

Opportunity Drives through Sol 410

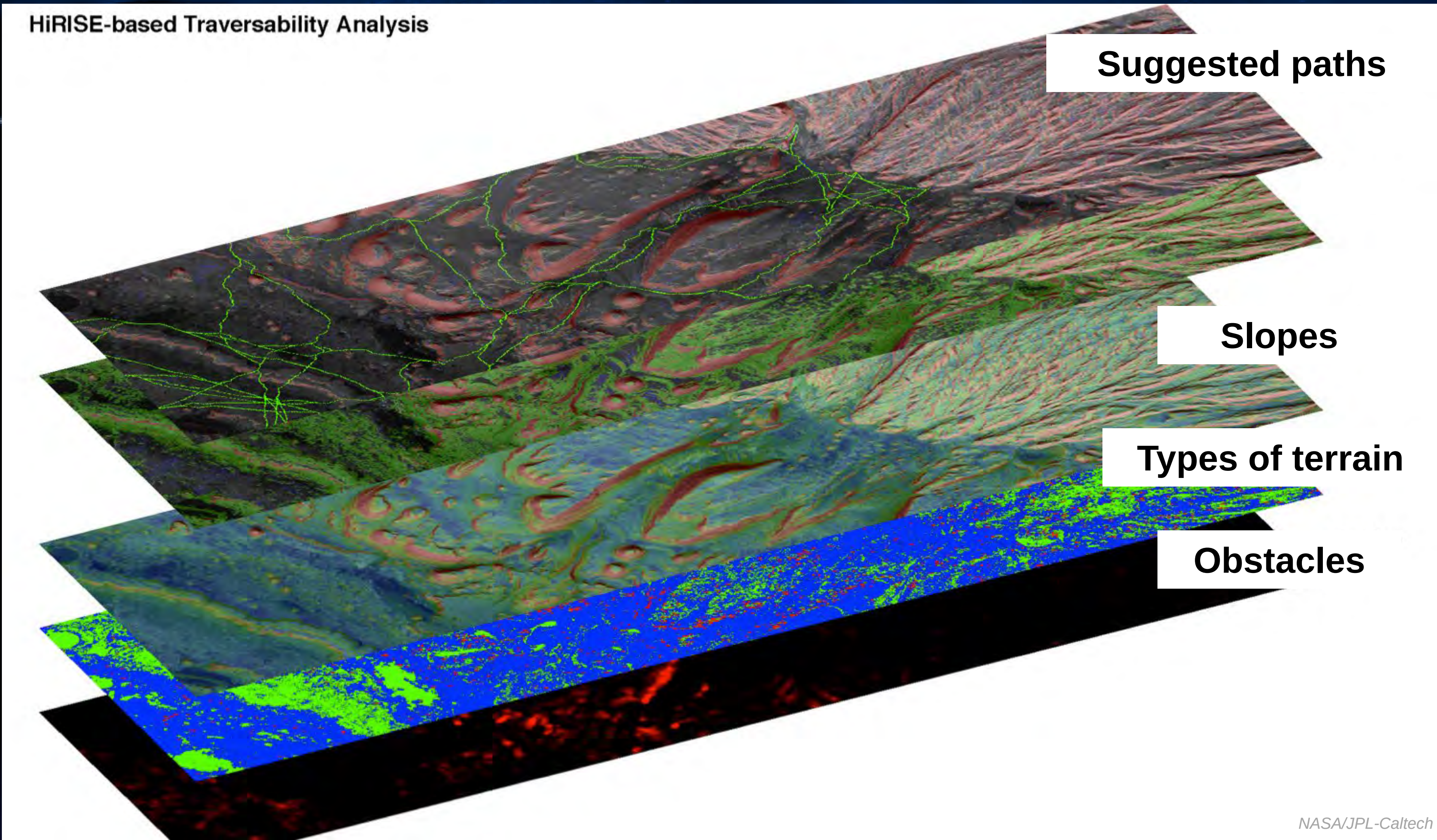


NASA/JPL/MSSS

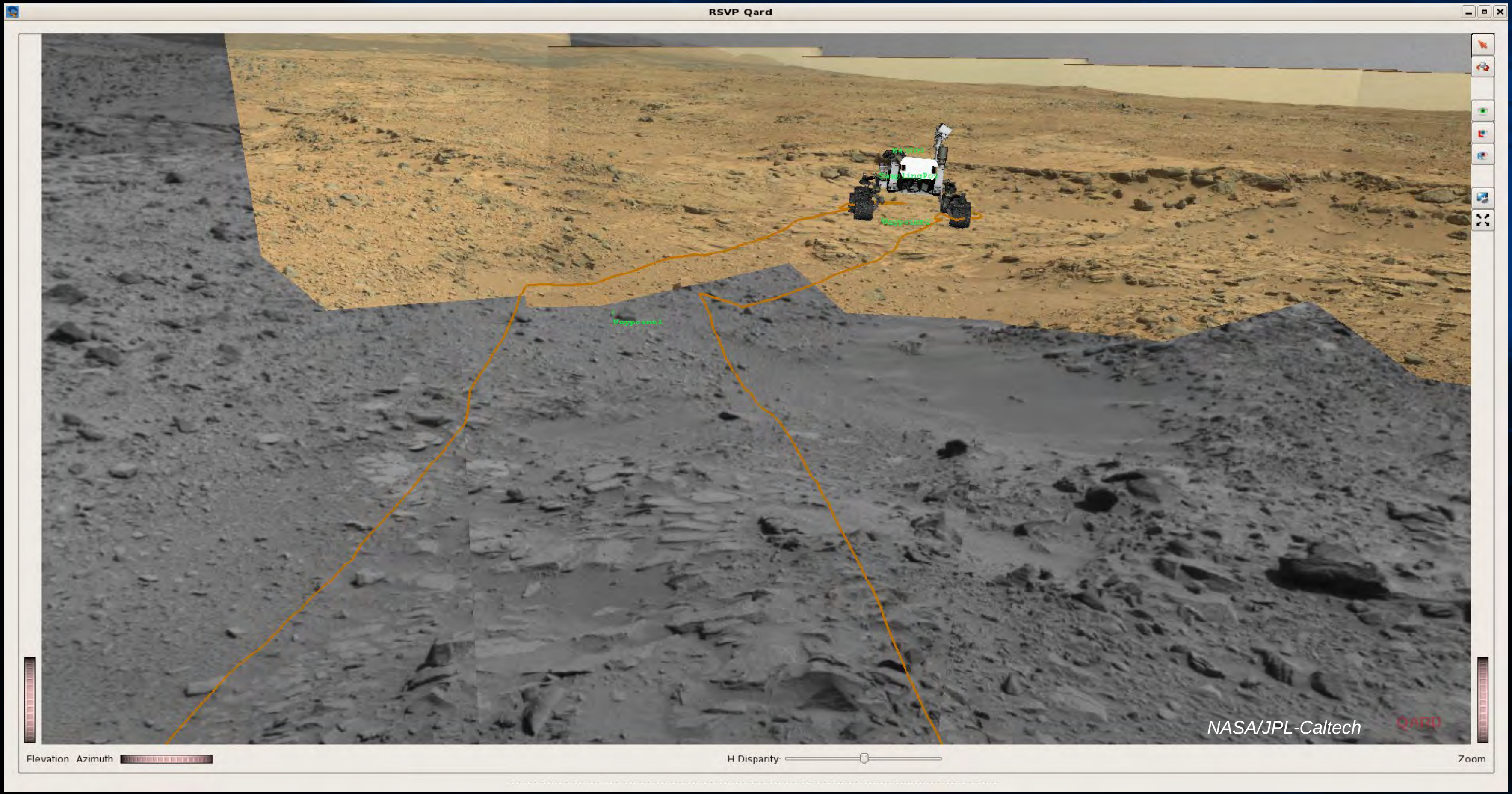
NASA/JPL-Caltech

Driving Modes:
Blind
Autonav
Visodom

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



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

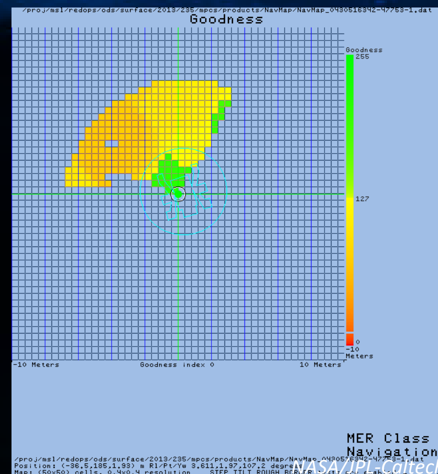


For "directed driving," drivers command the rover to move a certain distance over ground that they know is safe.

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!

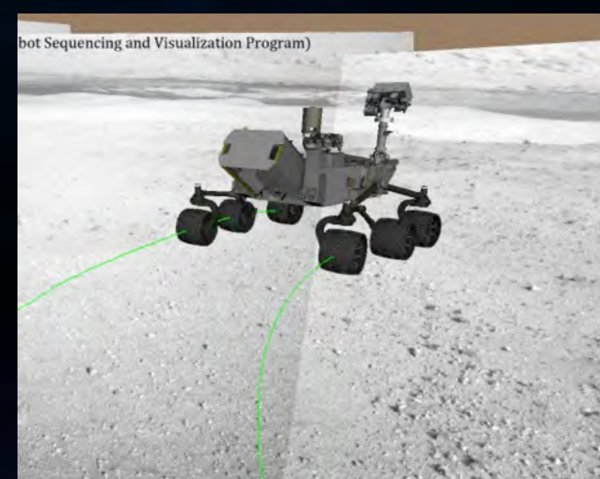
Curiosity Lets Human Drivers Choose the Level of Autonomy on Each Drive

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!***

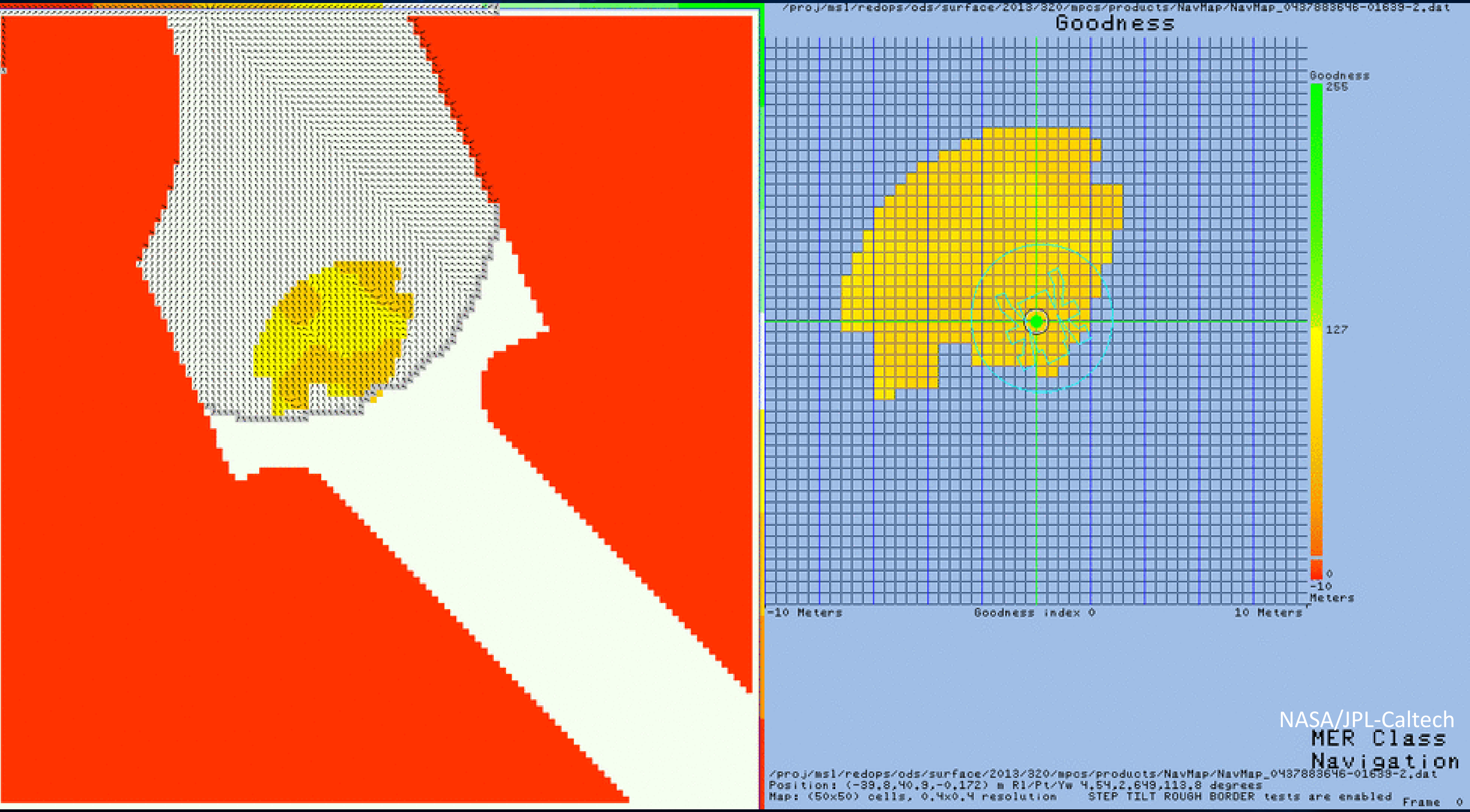
On sol 455, Curiosity Tried Multi-sol Driving again

- 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.

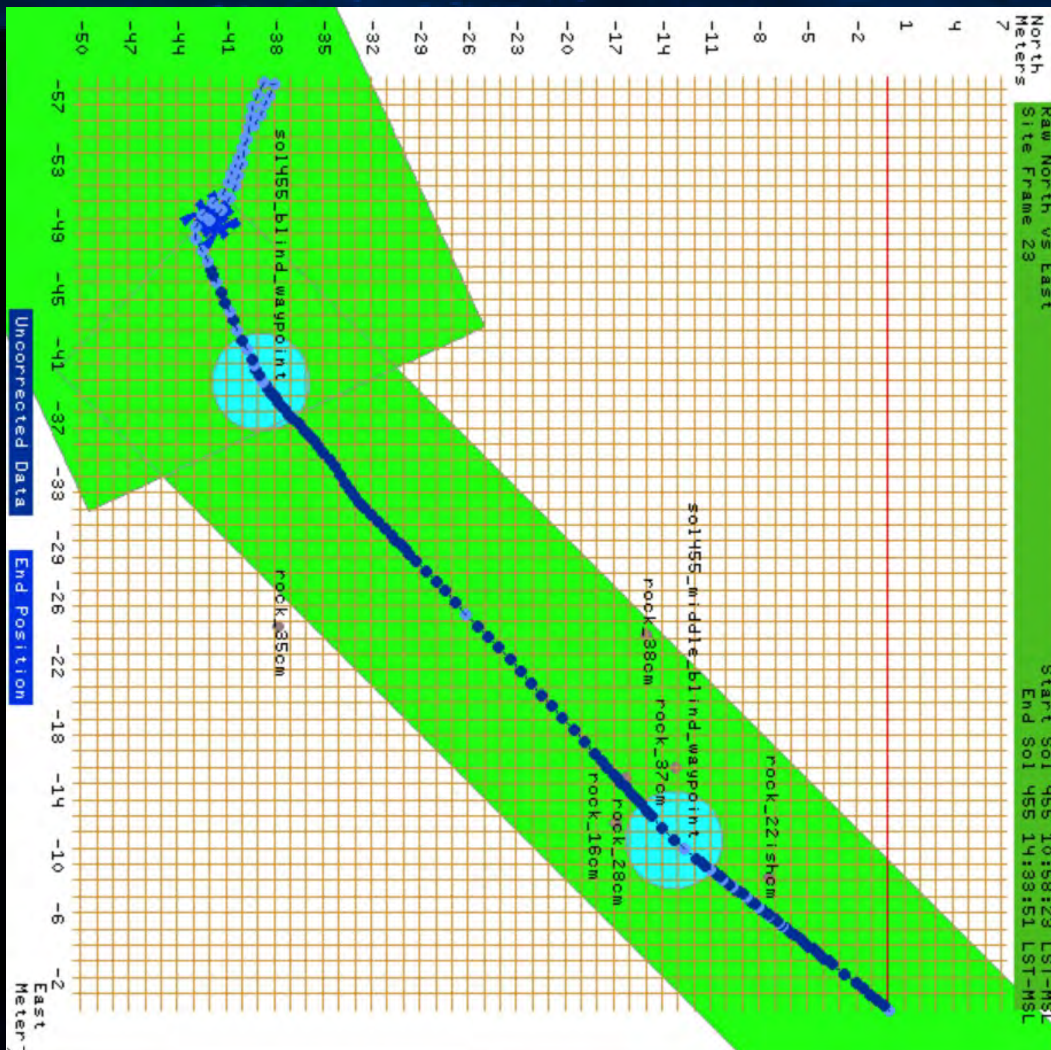
A Rover’s-eye view of the Autonomous Portion of the sol 455 drive

11:59:02___./ImgImageLocoNl_0437883156-15288-1.pds

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

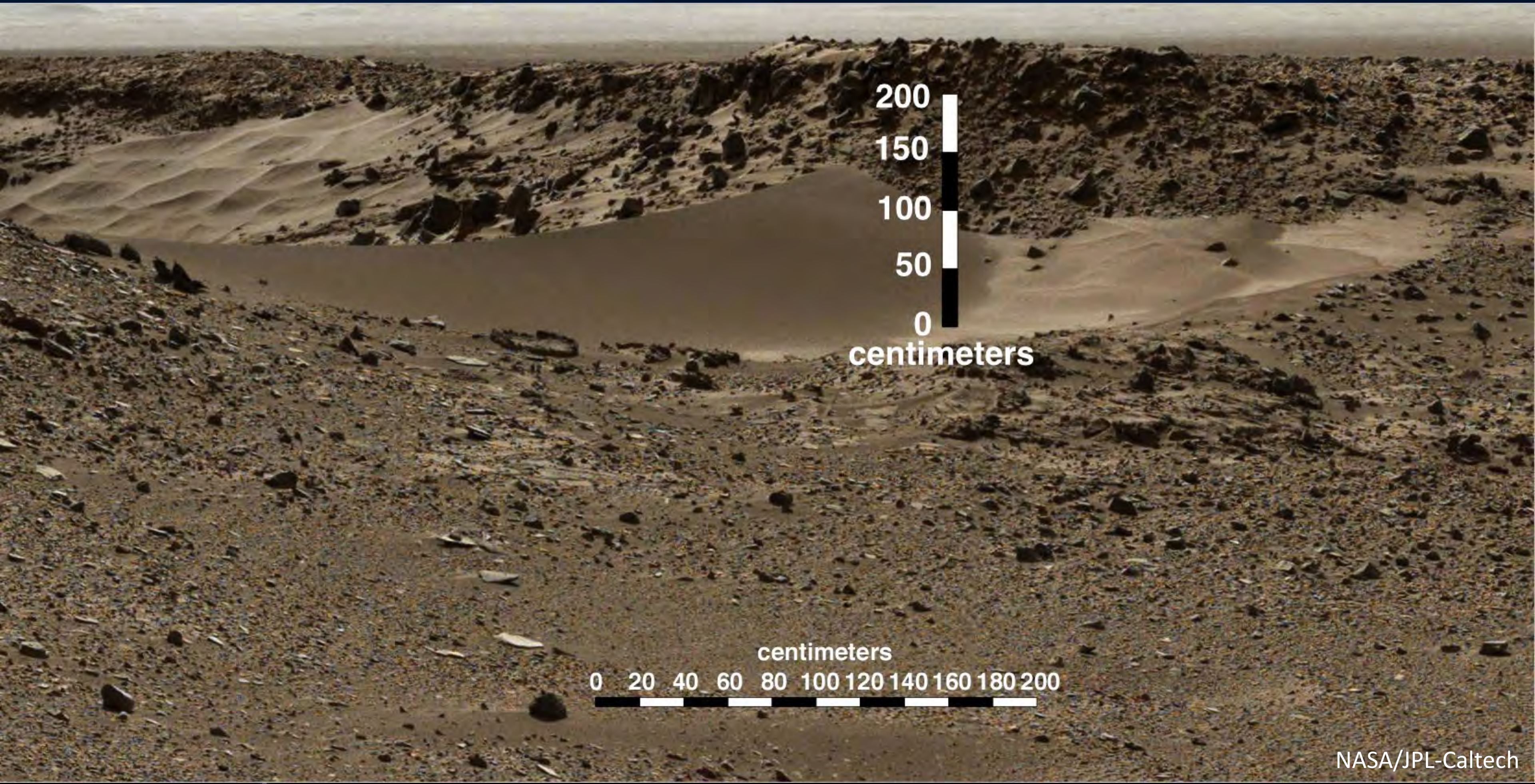


On sol 455, Curiosity encountered a small crater and began to drive around it



Small light blue dots represent the imaging steps

Sol 533-535: Dingo Gap

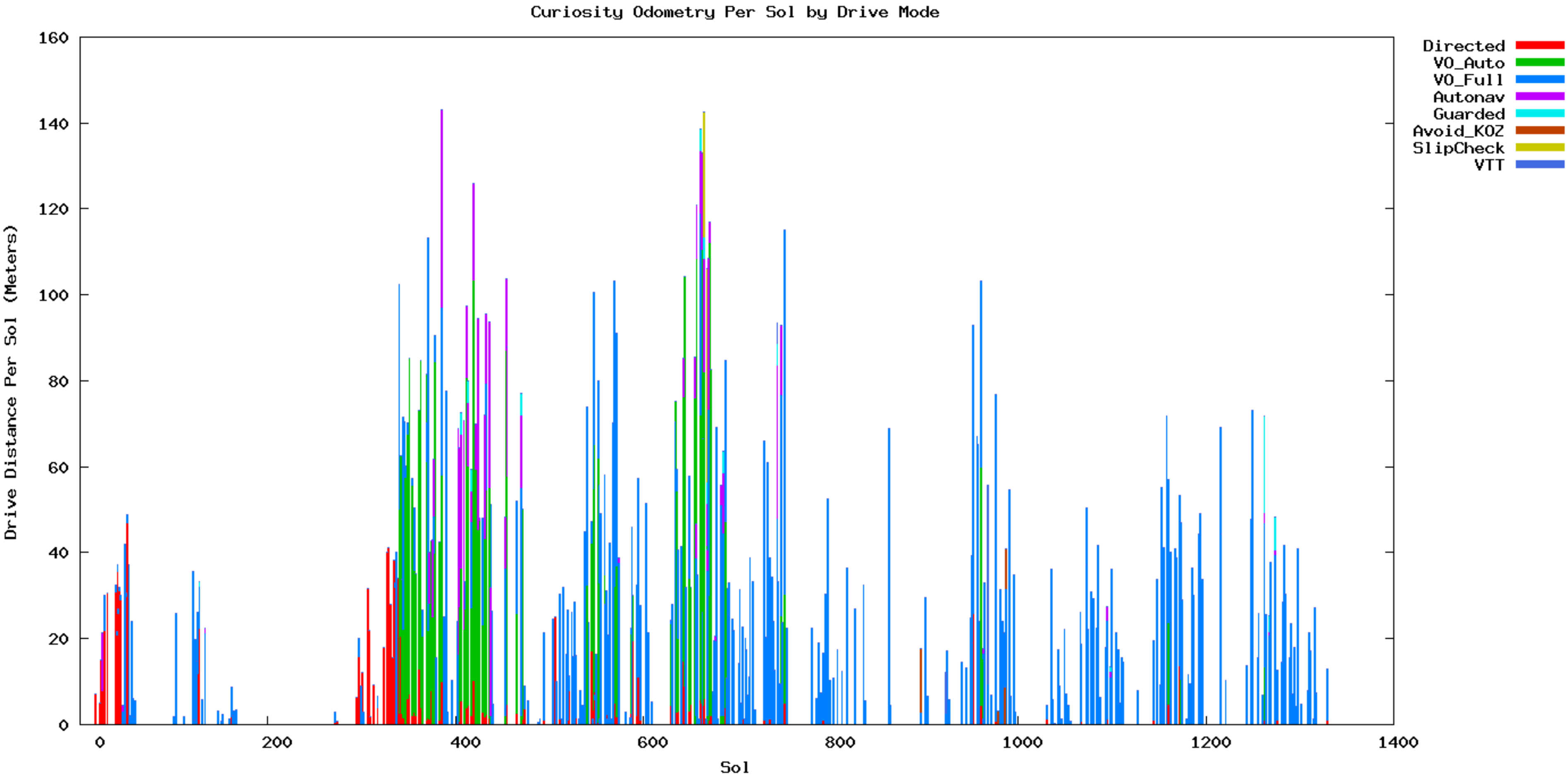


Sol 535: Climbing Over

NASA/JPL-Caltech

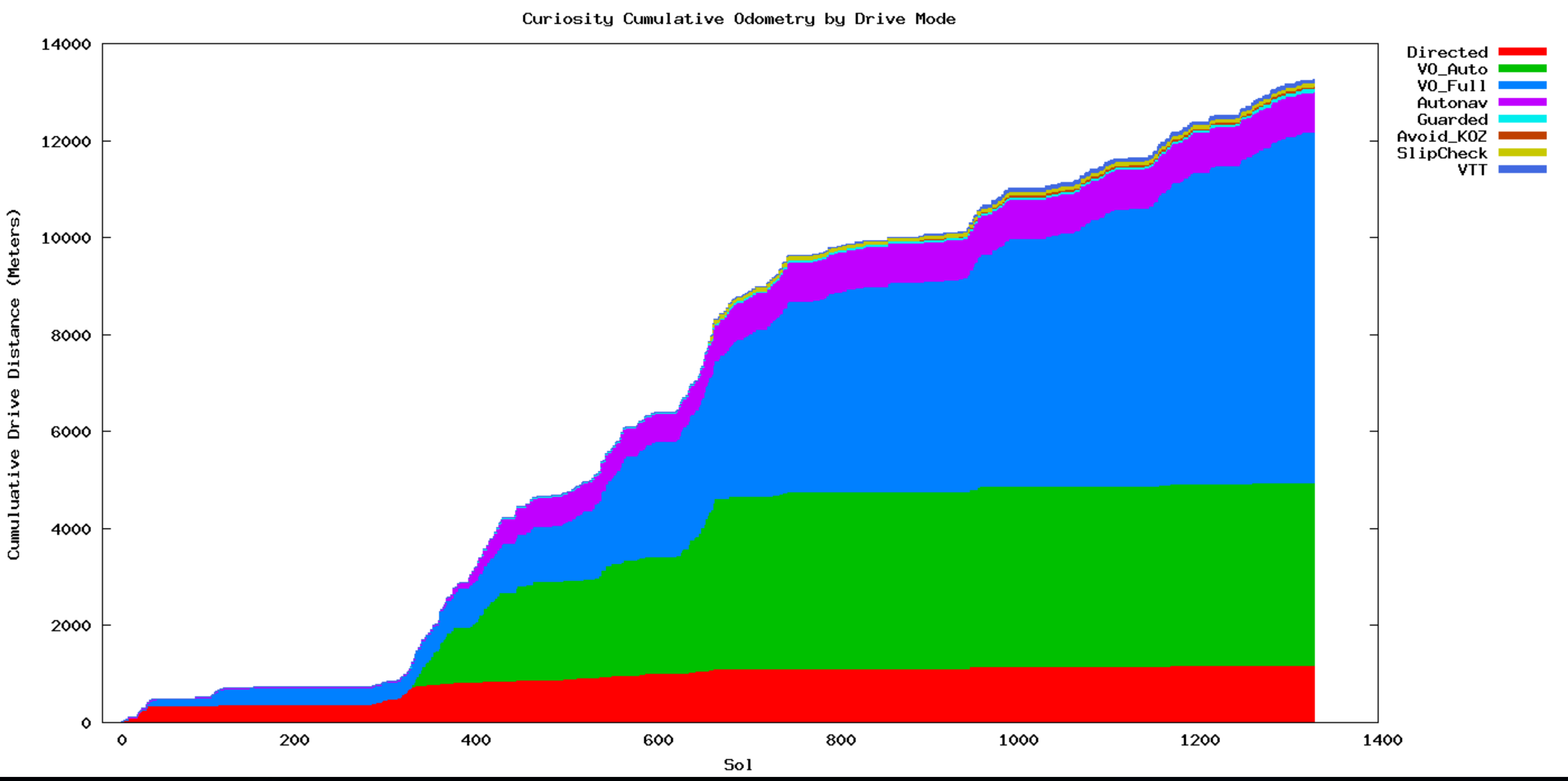
Statistics through sol 1330

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

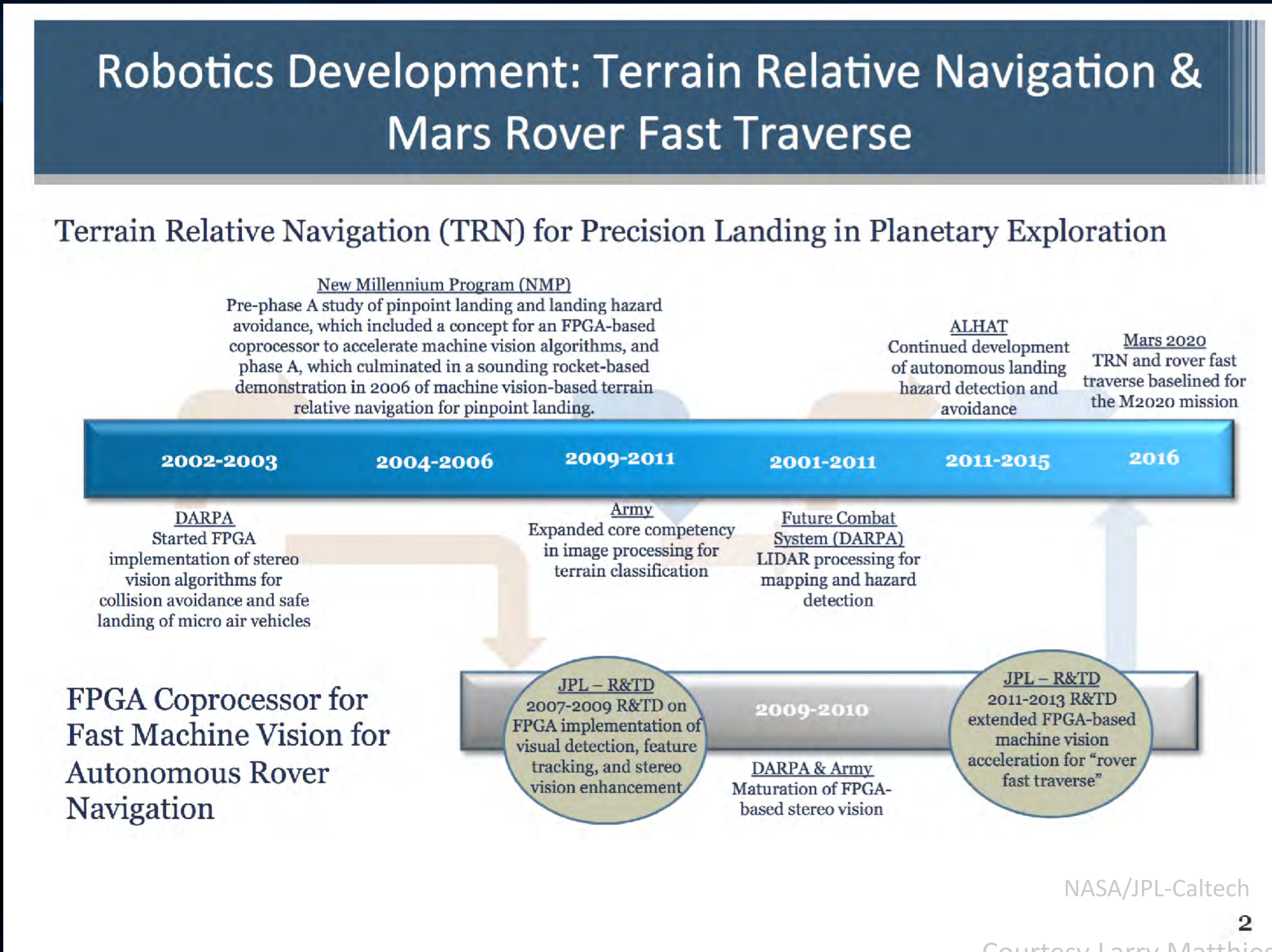
Some MSL Onboard Capabilities

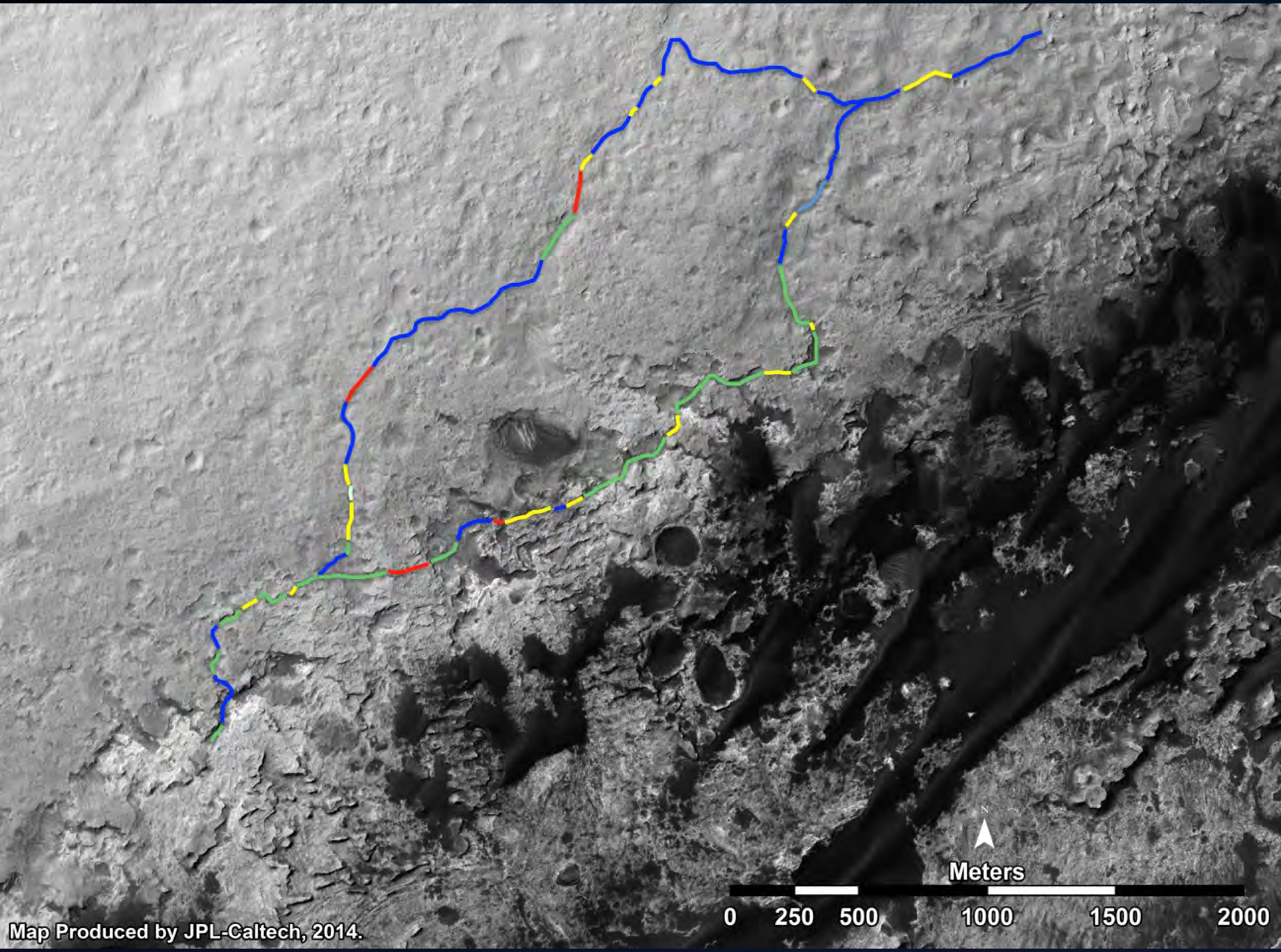
- Primary Mission
  - Local Path Selection and Global Path Planner - Field D*
  - Dense Stereo Vision for …
  - … Terrain Assessment
  - AutoNav: Hazard Detection and Avoidance
  - Visual Odometry
- Post-landing FSW updates
  - Visual Terrain Tracking
  - Autonomous Science – e.g., Dust Devil / Cloud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

What's Next is up to You!

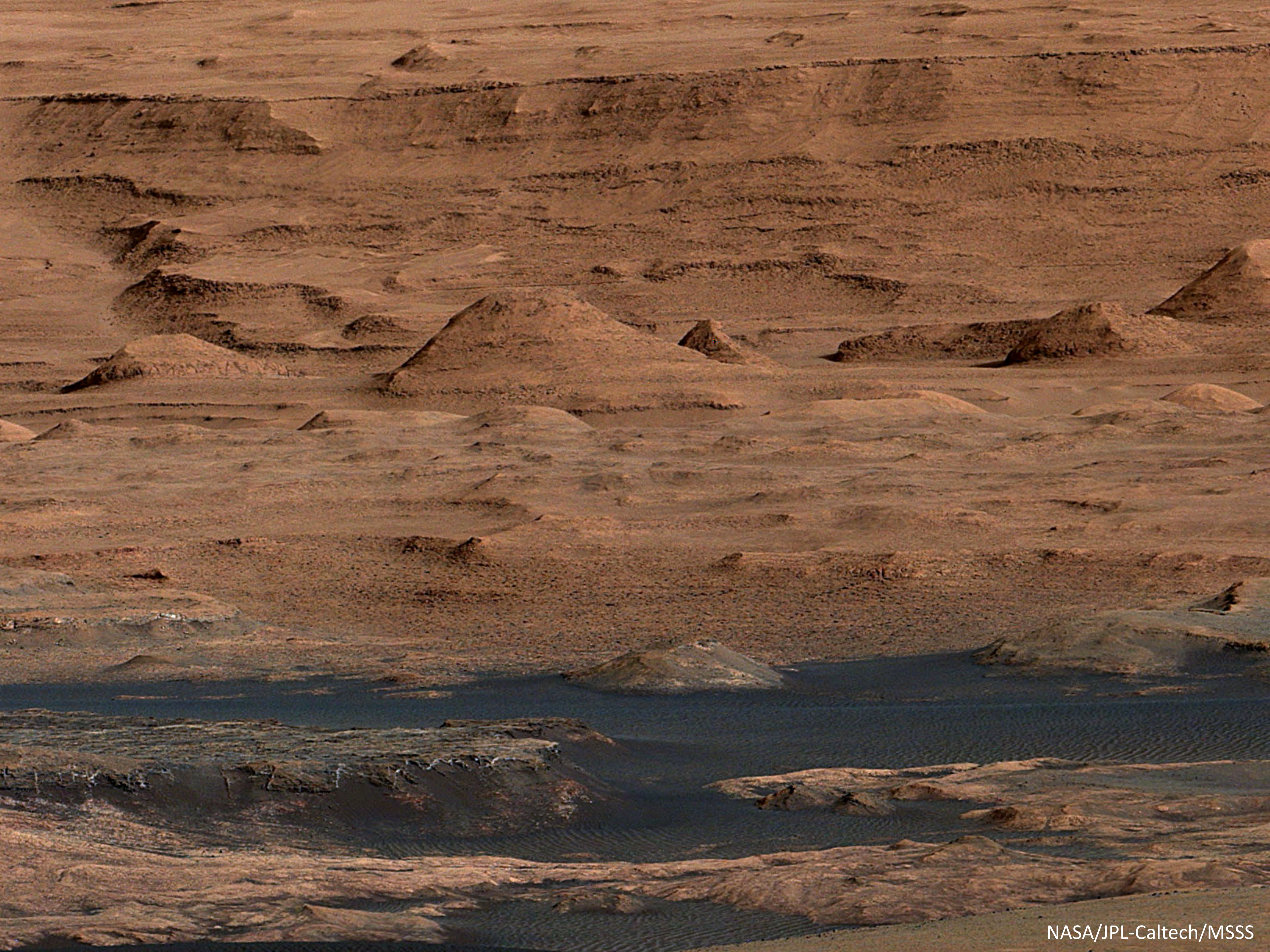
- Technology transfer into flight has several paths
- People: Join a flight project to support tech transfer
- Tech Push: MER 4th flight software release was coordinated as a tech transfer push by Project and Line Management
- Tech Pull: Anomalies are opportunities!

Navigation FGPA Coprocessors



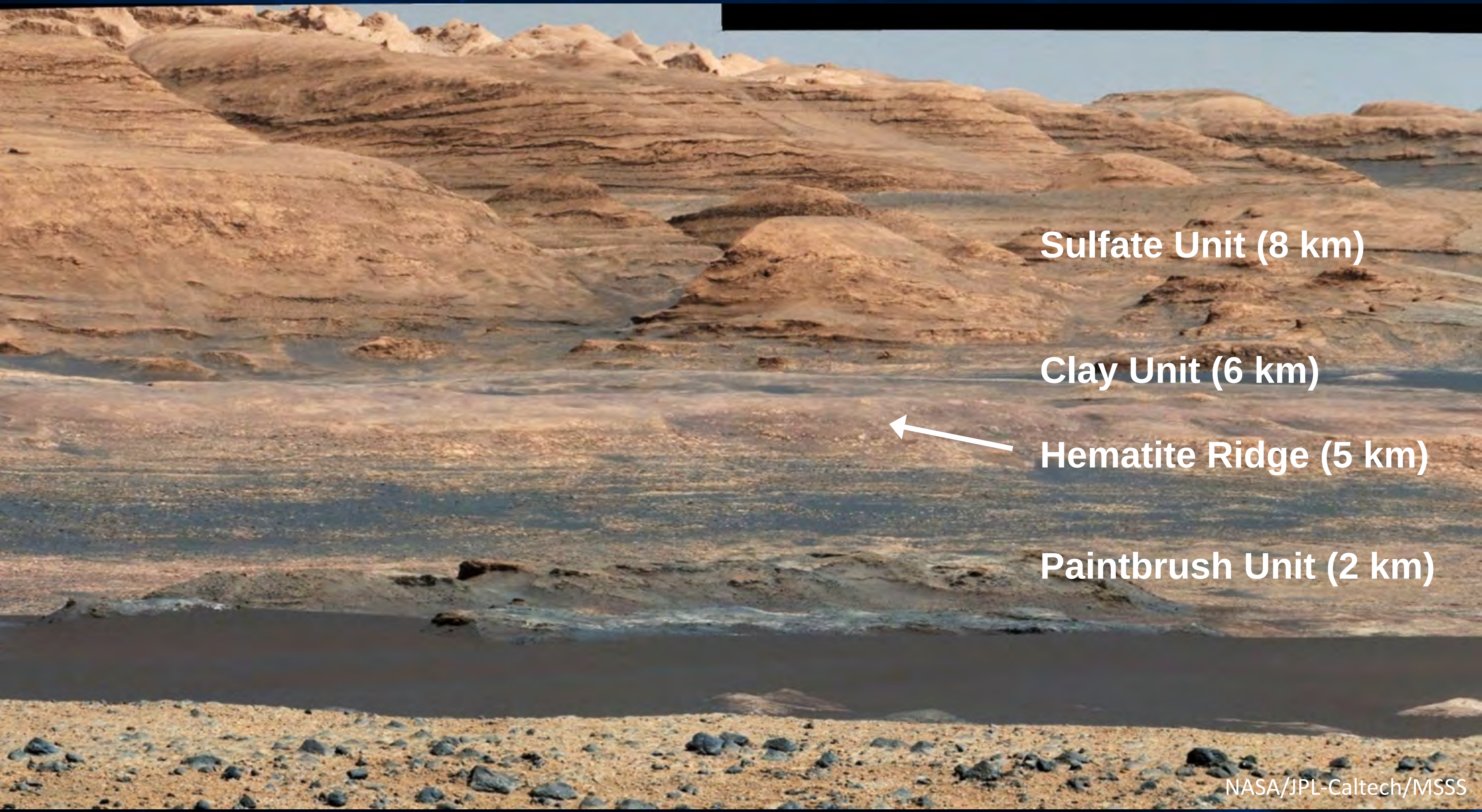

N
Meters
0
250
500
1000
1500
2000
Map Produced by JPL-Caltech, 2014.

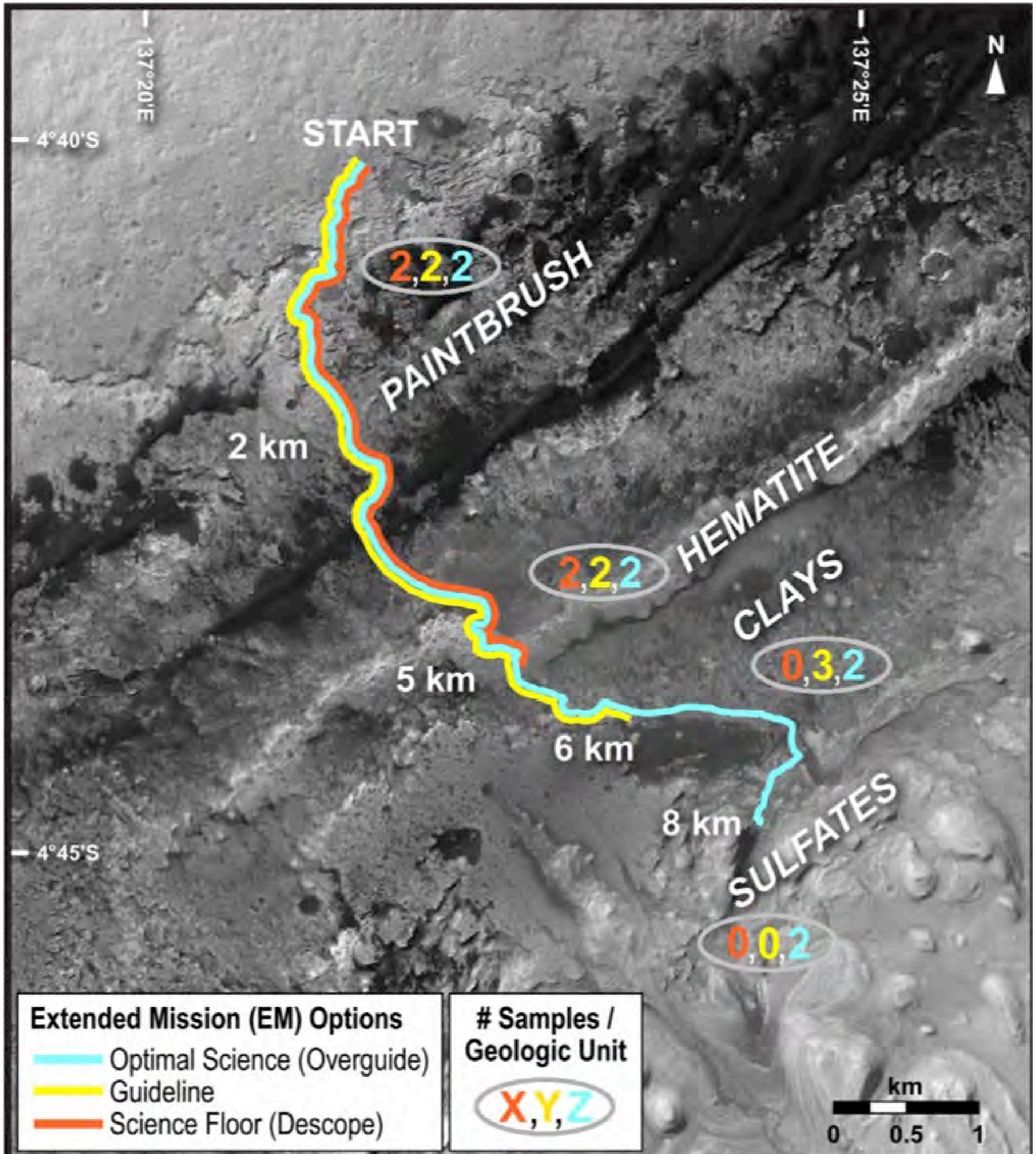
The Road Ahead



NASA/JPL-Caltech/MSSS

Targets for Exploration





to contain export controlled technical data.