Planetary Rover Systems: Sojourner to MSL

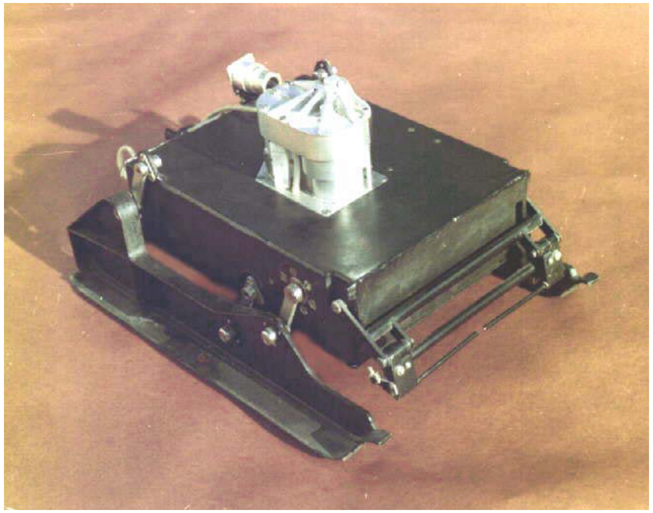
Mark Maimone
Jet Propulsion Laboratory
California Institute of Technology

Exploring Mars: Why Send Rovers?

- **Rovers complement orbital and fixed-lander assets**
  - Mobility enables precision placement of high fidelity *in situ* sensors
  - A large number of sites spanning kilometers can be sampled
  - Rovers enable opportunistic discovery and investigation of features not visible from orbit
  - Every drive gives you a “new landing site” to explore
- **Autonomous robotic capabilities mitigate communication delays**
  - Joysticking is impractical with round trip delays of 8-42 minutes
  - Logistics in the scheduling of Deep Space Network facilities limit the number of command cycles (nominally just one uplink per day)
  - *SOLUTION*: Onboard autonomous processing means a rover can operate safely even in areas not previously viewed in high resolution

Early Attempts, Research Rovers

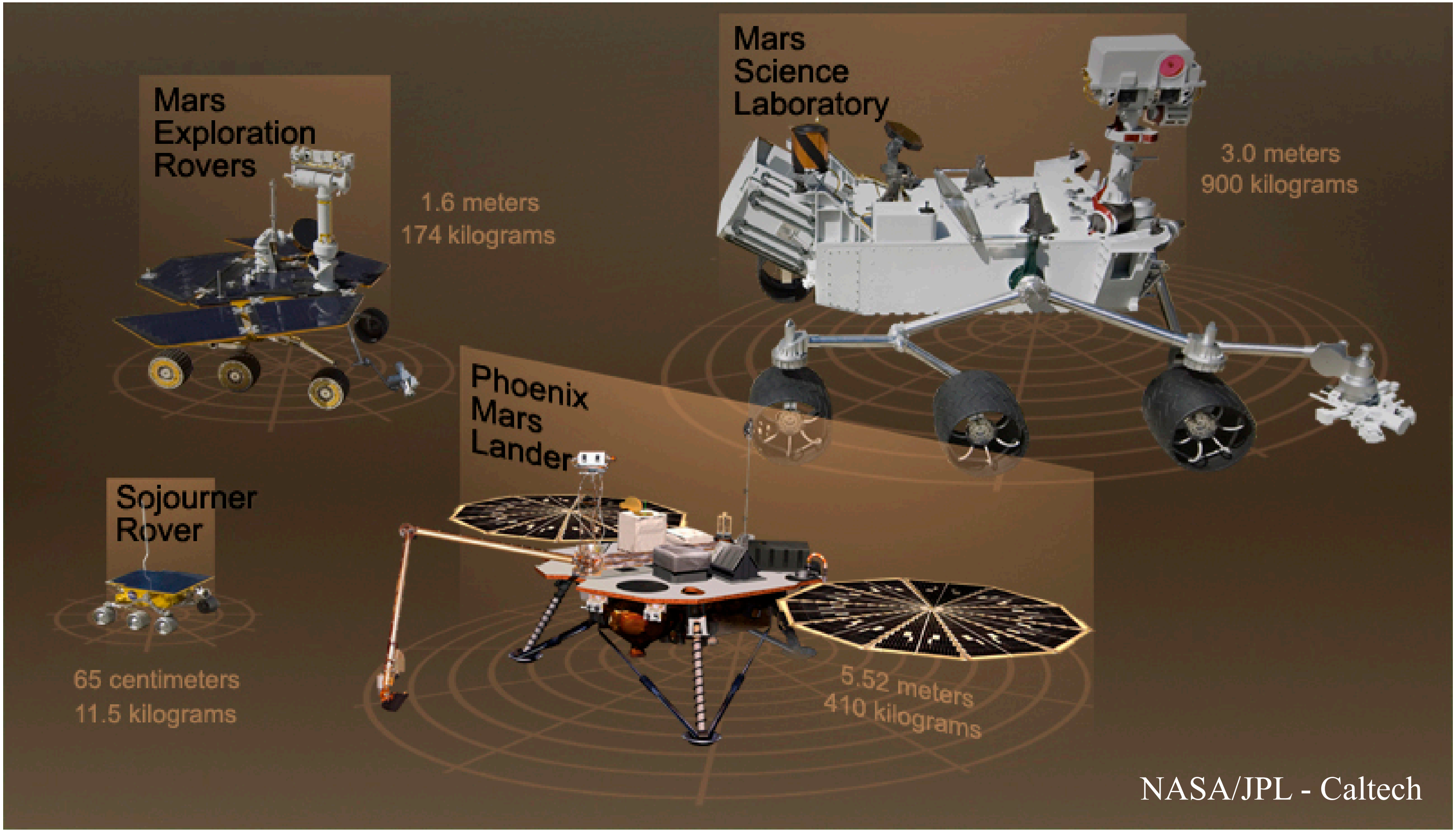
In the early 1970s the then-Soviet Union sent two small rovers to the Martian surface in Mars-2 and Mars-3 missions. Unfortunately neither mission lasted long enough to send back rover data.



B. Muirhead, *Mars Rovers: Past and Future*, IEEE Aerospace Conference, Big Sky, Montana March 6-13, 2004 has an overview of the 1960's - 1990's research programs in the US

Several Planetary Rover Workshops over the past 12 years, e.g.
`http://ewh.ieee.org/conf/icra/2008/workshops/PlanetaryRovers/`

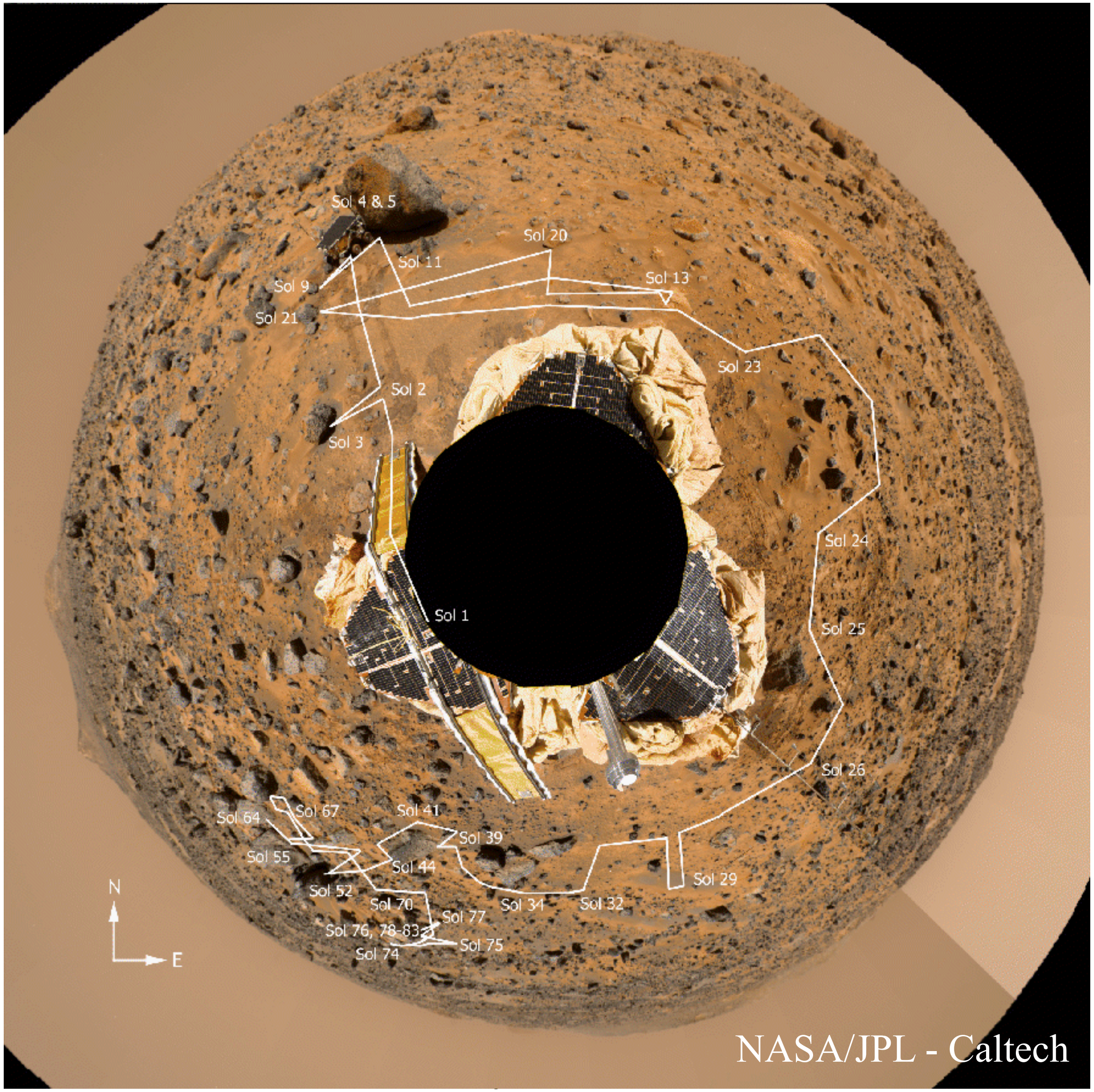
Recent and Future NASA Mars Surface Vehicles



NASA/JPL - Caltech

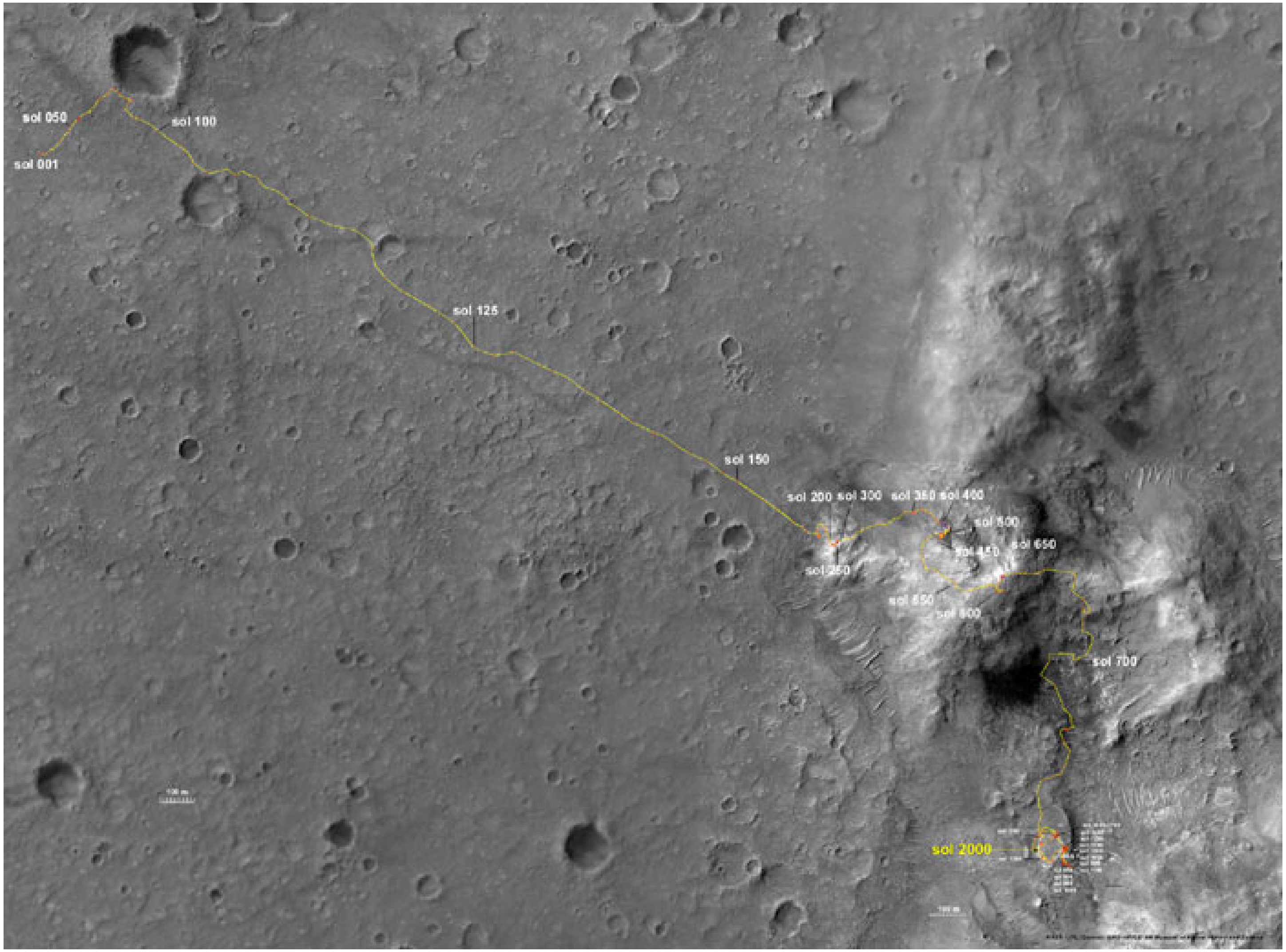
How Far Can They Drive?

Sojourner's Drive Path: 0.1 km in 0.3 years



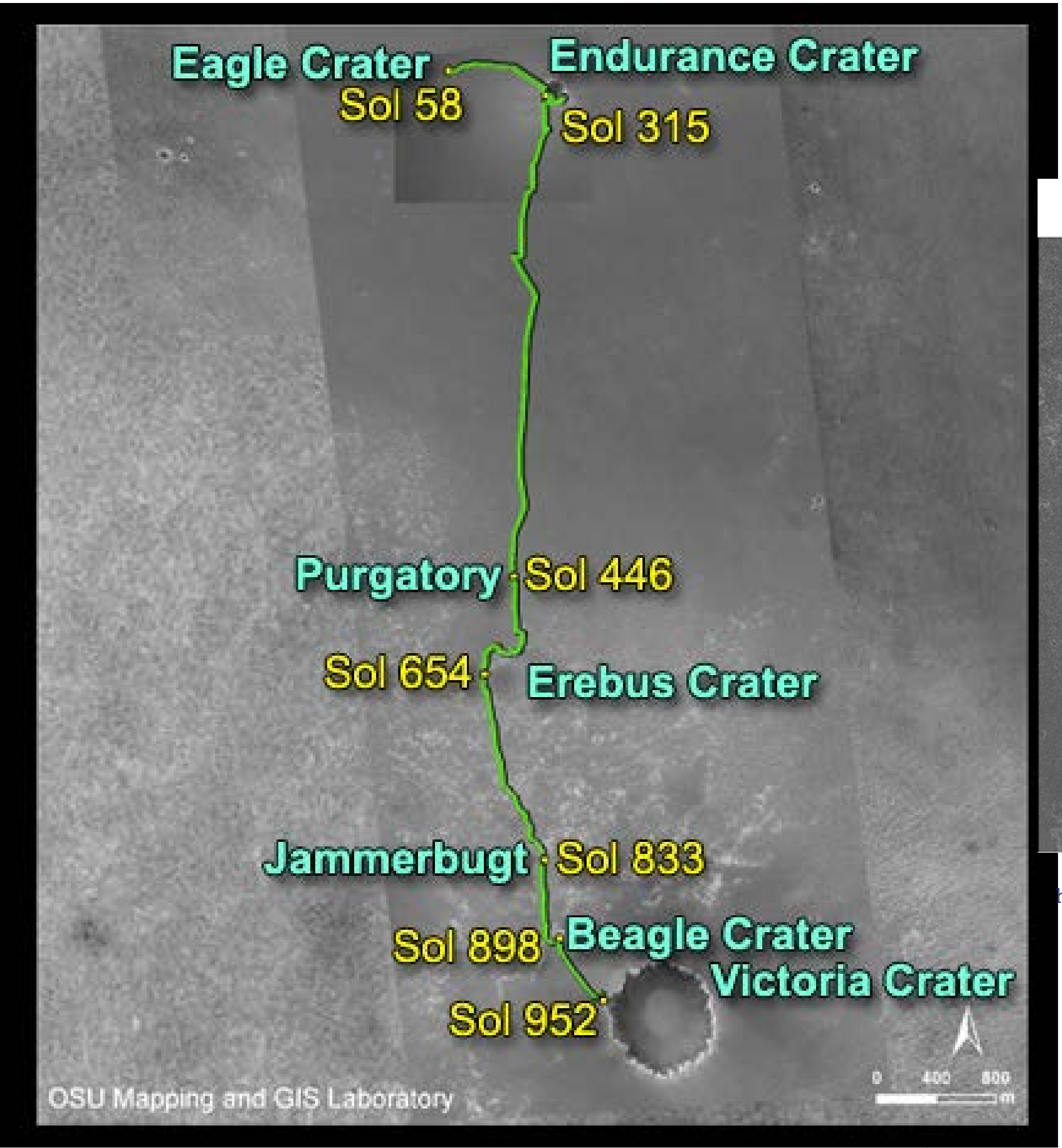
NASA/JPL - Caltech

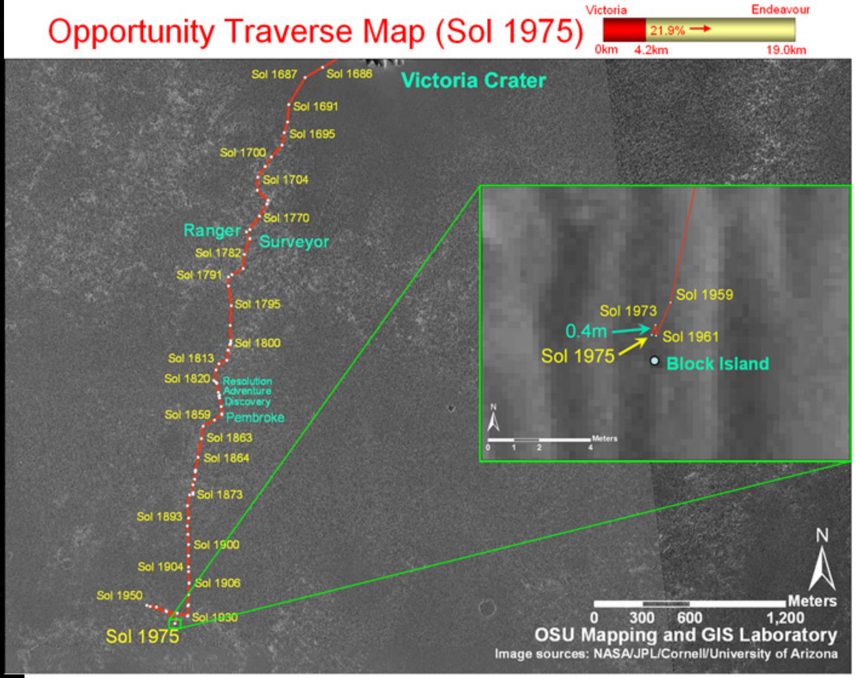
Spirit's Drive Path: 7.7 km in 5.6 years



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

Opportunity’s Drive Path: 17.2 km in 5.5 years





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

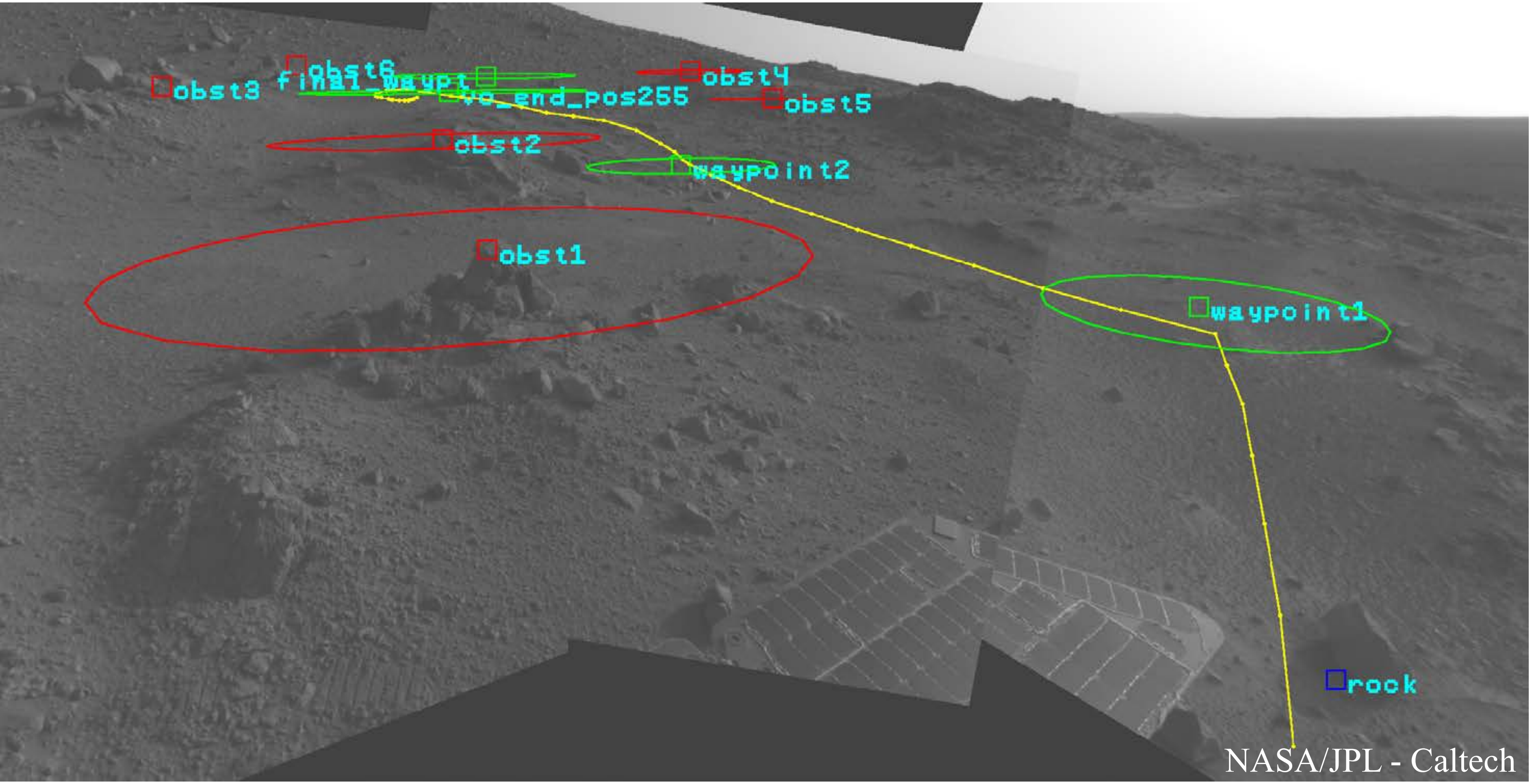
How Do We Choose Where to Drive?

3D Terrain visualization

QuickTime™ and a
Animation decompressor
are needed to see this picture.

Courtesy of
Frank Hartman
NASA/JPL
Caltech

Directed Driving is Complicated



NASA/JPL - Caltech

Sol A-436

Simulating the Planned Drive

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Spirit
Sol 74

25 m
Blind

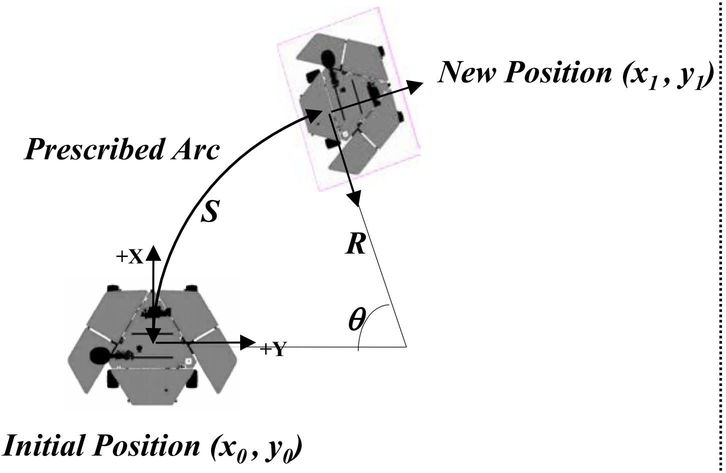
9 m
Autonomous

Courtesy of
Frank Hartman
NASA/JPL
Caltech

MER Driving Commands

Basic Mobility

Arc (distance, delta-heading, mode, timeout)

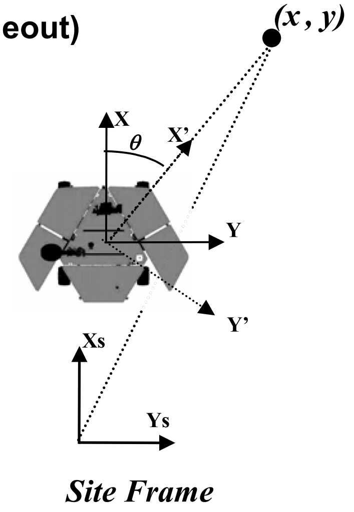


Move along circular arc or straight line path of commanded length - Open-loop relative to on-board position/heading estimate

Turn_absolute (angle,mode, timeout)

Turn_relative (angle,mode, timeout)

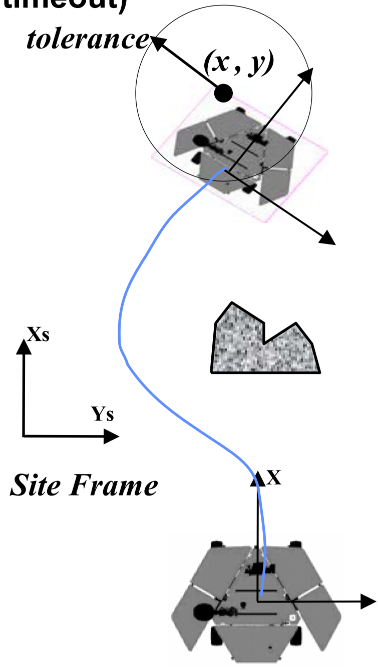
Turn_to (x,y, offset, mode, timeout)



Turn in-place about rover center to commanded heading - Closed-loop around IMU based heading estimate

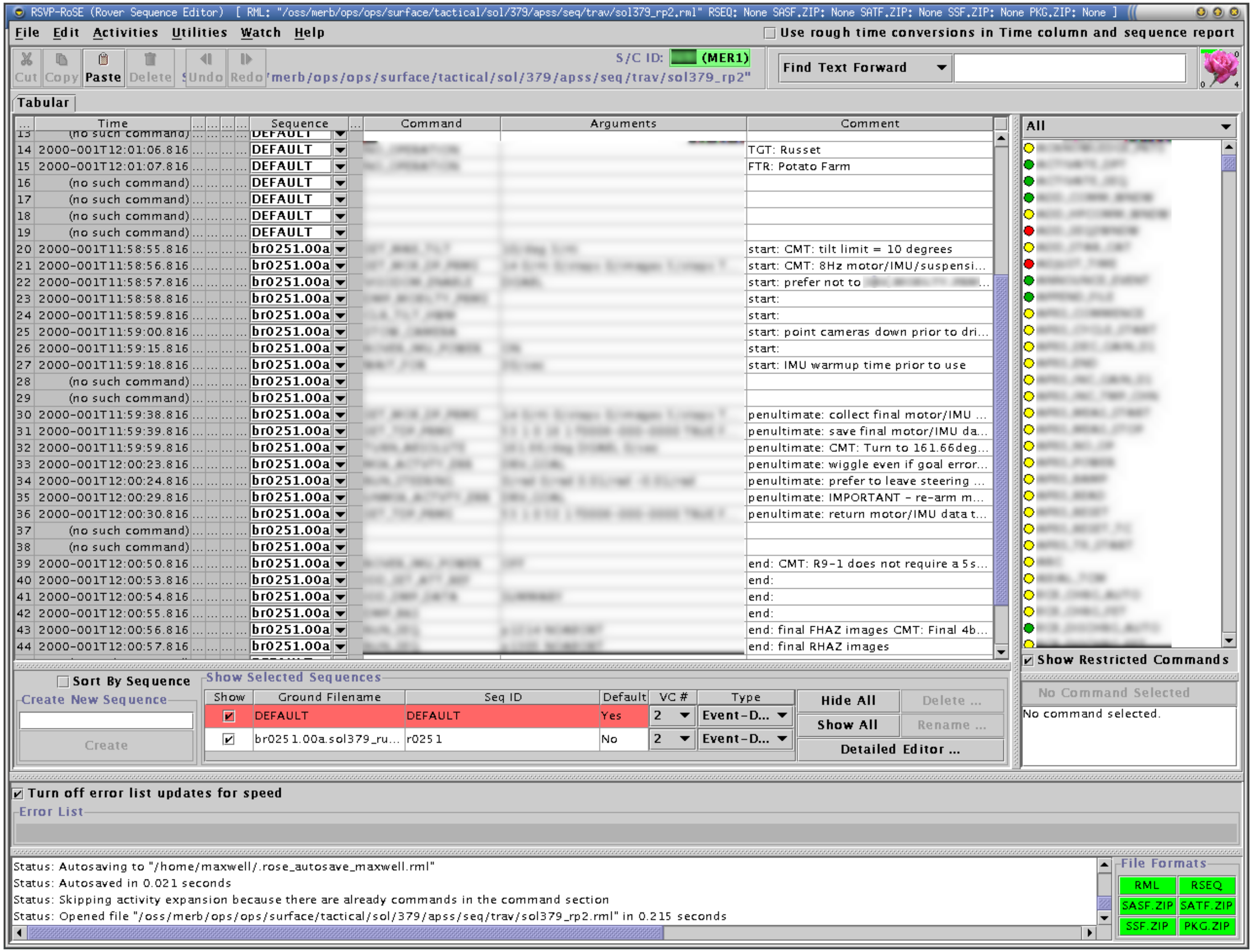
Autonomous Navigation

Goto_waypoint (x, y, tolerance, mode, timeout)



Autonomous traverse toward a commanded waypoint with on-board hazard detection using stereo vision - Closed-loop around position and heading estimate

Event-driven Command Sequences



☐ Use rough time conversions in Time column and sequence report

S/C ID: (MER1) 'merb/ops/ops/surface/tactical/sol/379/apss/seq/trav/sol379_rp2"

…	Time	…	…	…	…	Sequence	…	Command	Arguments	Comment
13	(no such command)	…	…	…	…	DEFAULT				
14	2000-001T12:01:06.816	…	…	…	…	DEFAULT				TGT: Russet
15	2000-001T12:01:07.816	…	…	…	…	DEFAULT				FTR: Potato Farm
16	(no such command)	…	…	…	…	DEFAULT				
17	(no such command)	…	…	…	…	DEFAULT				
18	(no such command)	…	…	…	…	DEFAULT				
19	(no such command)	…	…	…	…	DEFAULT				
20	2000-001T11:58:55.816	…	…	…	…	br0251.00a				start: CMT: tilt limit = 10 degrees
21	2000-001T11:58:56.816	…	…	…	…	br0251.00a				start: CMT: 8Hz motor/IMU/suspensi…
22	2000-001T11:58:57.816	…	…	…	…	br0251.00a				start: prefer not to …
23	2000-001T11:58:58.816	…	…	…	…	br0251.00a				start:
24	2000-001T11:58:59.816	…	…	…	…	br0251.00a				start:
25	2000-001T11:59:00.816	…	…	…	…	br0251.00a				start: point cameras down prior to dri…
26	2000-001T11:59:15.816	…	…	…	…	br0251.00a				start:
27	2000-001T11:59:18.816	…	…	…	…	br0251.00a				start: IMU warmup time prior to use
28	(no such command)	…	…	…	…	br0251.00a				
29	(no such command)	…	…	…	…	br0251.00a				
30	2000-001T11:59:38.816	…	…	…	…	br0251.00a				penultimate: collect final motor/IMU …
31	2000-001T11:59:39.816	…	…	…	…	br0251.00a				penultimate: save final motor/IMU da…
32	2000-001T11:59:59.816	…	…	…	…	br0251.00a				penultimate: CMT: Turn to 161.66deg…
33	2000-001T12:00:23.816	…	…	…	…	br0251.00a				penultimate: wiggle even if goal error…
34	2000-001T12:00:24.816	…	…	…	…	br0251.00a				penultimate: prefer to leave steering …
35	2000-001T12:00:29.816	…	…	…	…	br0251.00a				penultimate: IMPORTANT - re-arm m…
36	2000-001T12:00:30.816	…	…	…	…	br0251.00a				penultimate: return motor/IMU data t…
37	(no such command)	…	…	…	…	br0251.00a				
38	(no such command)	…	…	…	…	br0251.00a				
39	2000-001T12:00:50.816	…	…	…	…	br0251.00a				end: CMT: R9-1 does not require a 5s…
40	2000-001T12:00:53.816	…	…	…	…	br0251.00a				end:
41	2000-001T12:00:54.816	…	…	…	…	br0251.00a				end:
42	2000-001T12:00:55.816	…	…	…	…	br0251.00a				end:
43	2000-001T12:00:56.816	…	…	…	…	br0251.00a				end: final FHAZ images CMT: Final 4b…
44	2000-001T12:00:57.816	…	…	…	…	br0251.00a				end: final RHAZ images

☑ Show Restricted Commands

No Command Selected

No command selected.

☐ Sort By Sequence

Create New Sequence

Show Selected Sequences

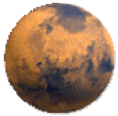
Show	Ground Filename	Seq ID	Default	VC #	Type
☑	DEFAULT	DEFAULT	Yes	2	Event-D...
☑	br0251.00a.sol379_ru...	r0251	No	2	Event-D...

☑ Turn off error list updates for speed

Error List

```
Status: Autosaving to "/home/maxwell/.rose_autosave_maxwell.rml"
Status: Autosaved in 0.021 seconds
Status: Skipping activity expansion because there are already commands in the command section
Status: Opened file "/oss/merb/ops/ops/surface/tactical/sol/379/apss/seq/trav/sol379_rp2.rml" in 0.215 seconds
```

**Courtesy of
Scott Maxwell
NASA/JPL
Caltech**



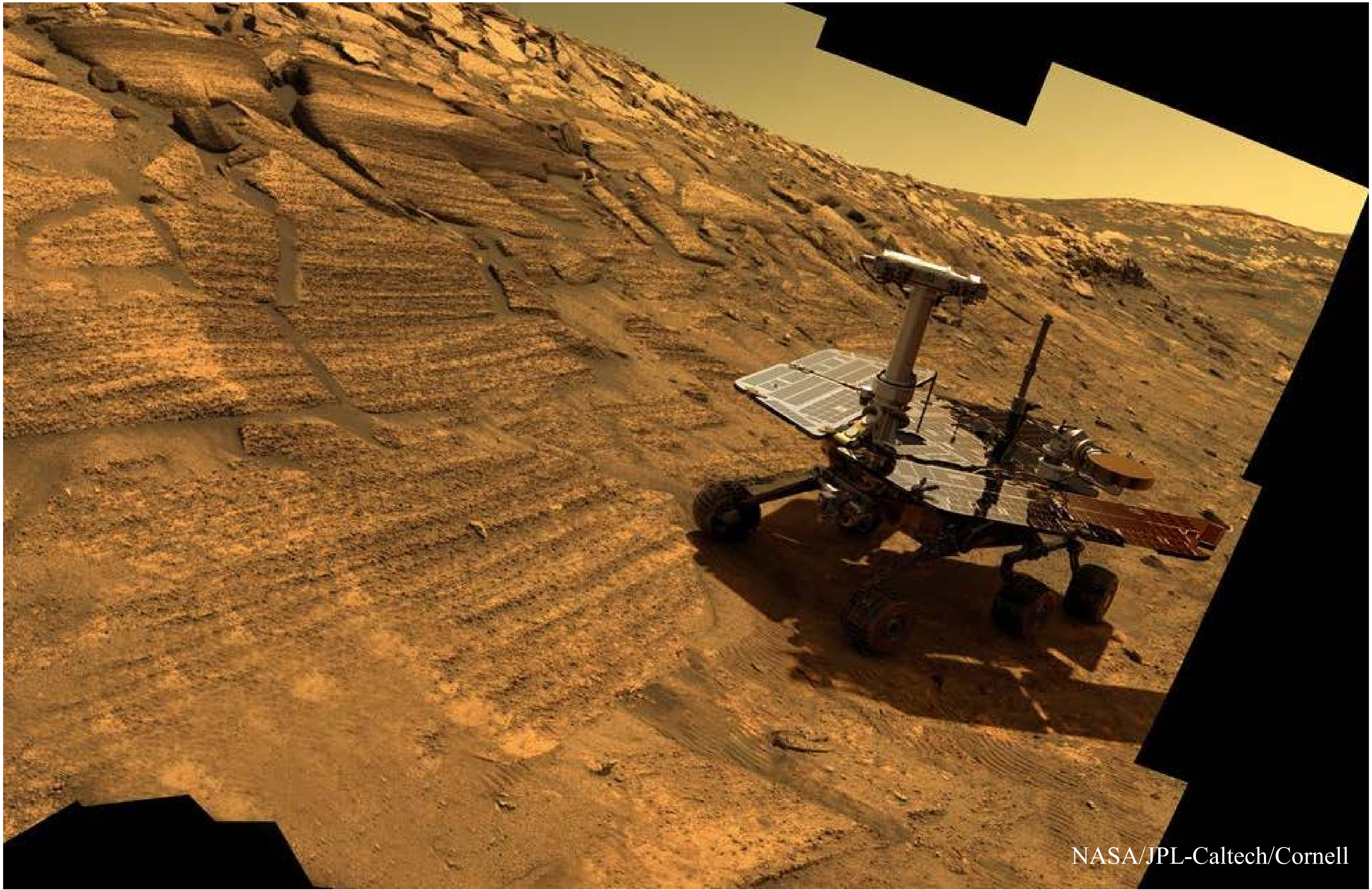
MER Driving Speeds

- 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.

Comparing Driving Speeds

All speeds in meters/hour	Sojourner	MER	MSL
Directed ("Blind") max mechanically attainable	24	180	210
Directed ("Blind") nominal (pauses, less than 100% speed)	14	120	~ 144
Hazard Avoidance	Not reported	10-35	Faster than MER
Visual Odometry	N/A	10	Faster than MER
Hazard Avoidance and Visual Odometry	N/A	5	Faster than MER

Pushing limits: Driving at 25-30 Degrees



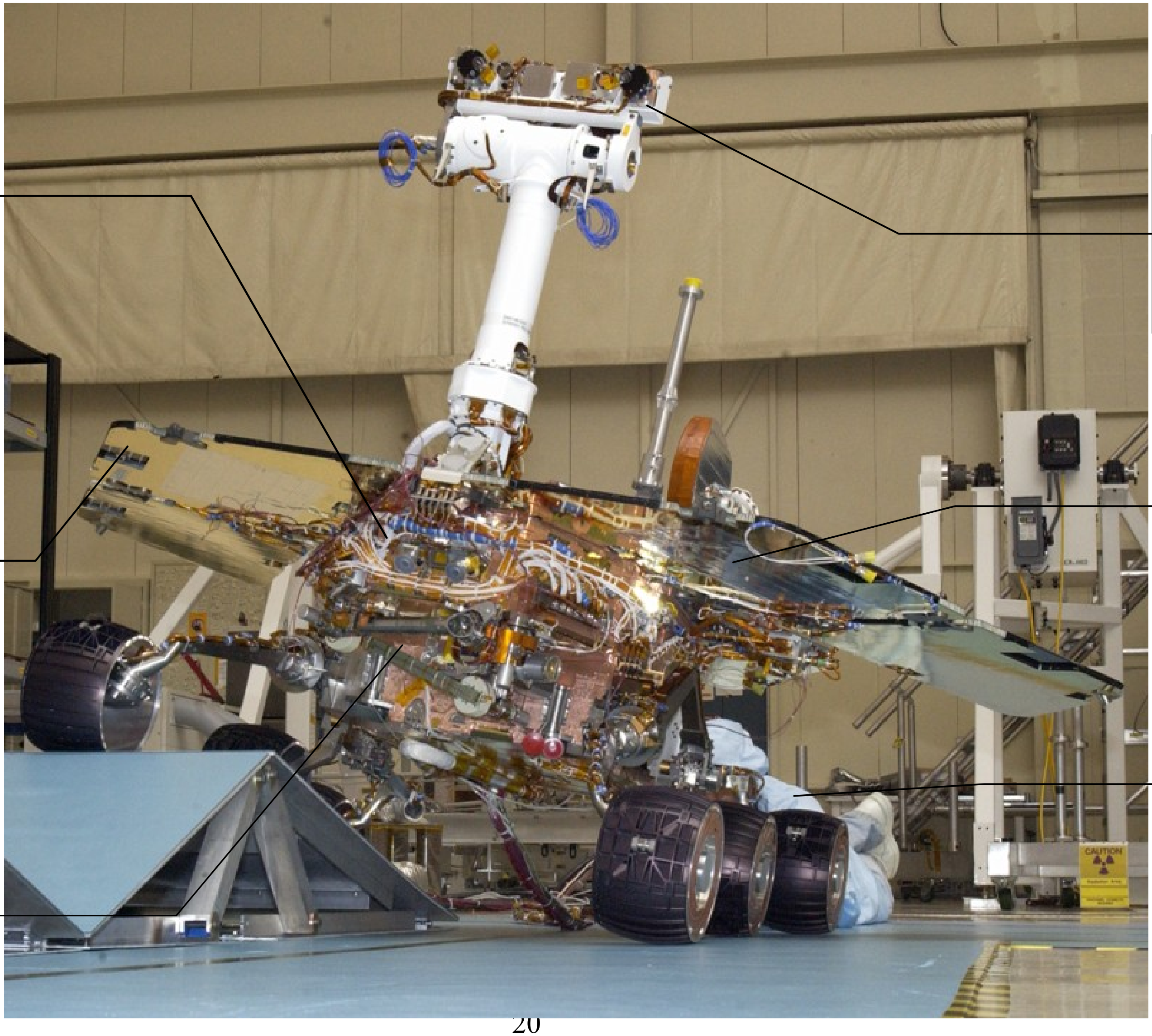
NASA/JPL-Caltech/Cornell

What Kind of Technology Do They Have?

Main Computer Comparison

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

MER Mobility Hardware



Wide FOV stereo HAZCAMs (front & rear) for on-board hazard detection

No bumpers/contact sensors on rover body or solar panels

IDD

Stereo NAVCAMS & PANCAMS used by ground team for planning. PANCAM used for sun based attitude update

IMU(internal) for attitude determination during motion

Six wheel rocker-bogie mobility system, steering at four corners

Onboard Autonomous Robotic Technologies

- **Geometric Hazard Detection and Avoidance**
  - Includes long range map-based D* optimal path planning
- **Visual Odometry - update position and attitude by comparing images taken before and after motion**
- **Visual Target Tracking - keep watching a ground-commanded target no matter what the drive does**
- **Autonomous Instrument Placement - safely deploy the instrument arm even in previously unseen areas**

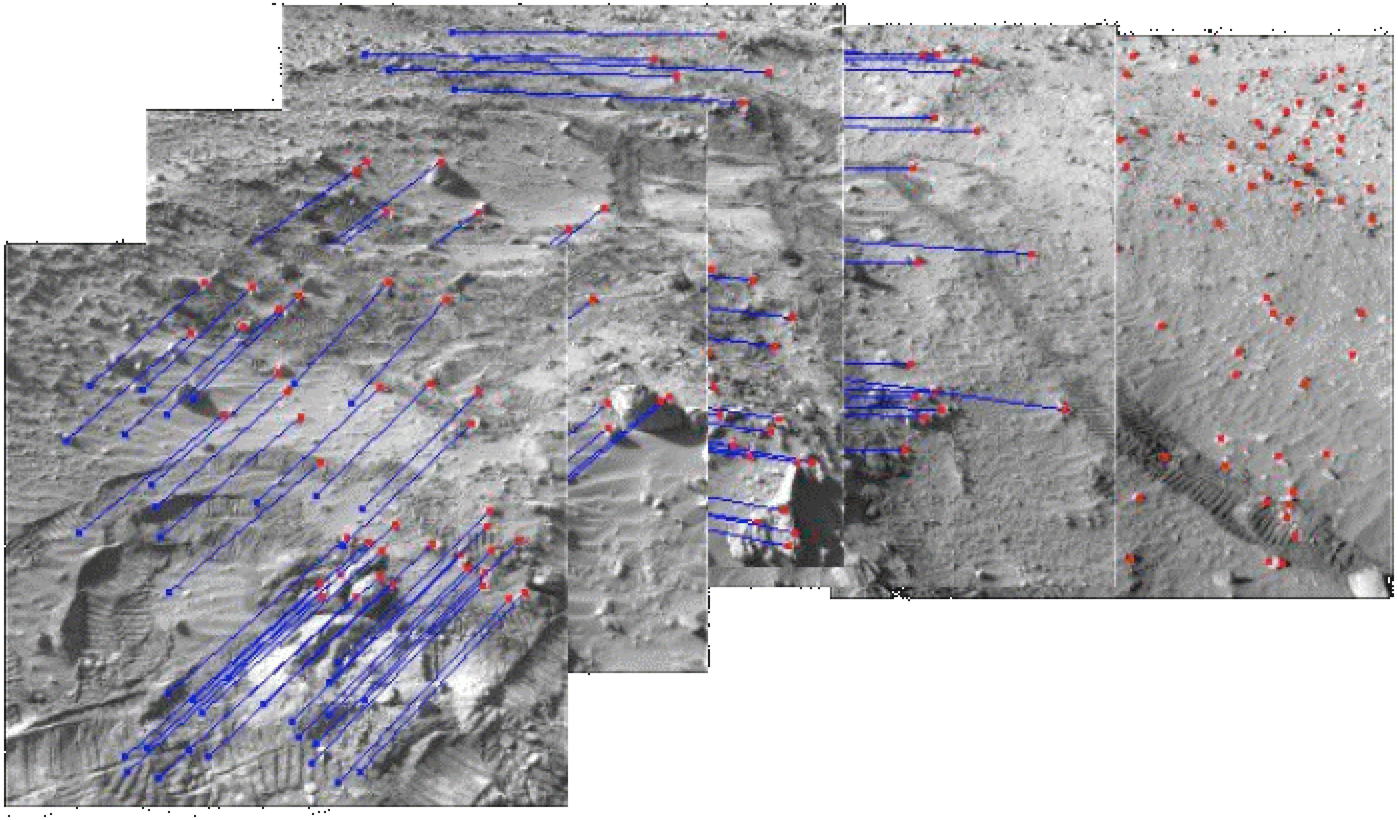
- **Onboard Autonomous Science - dust devil and cloud detection in images**

Detect and Avoid Geometric Hazards

QuickTime™ and a
H.264 decompressor
are needed to see this picture.

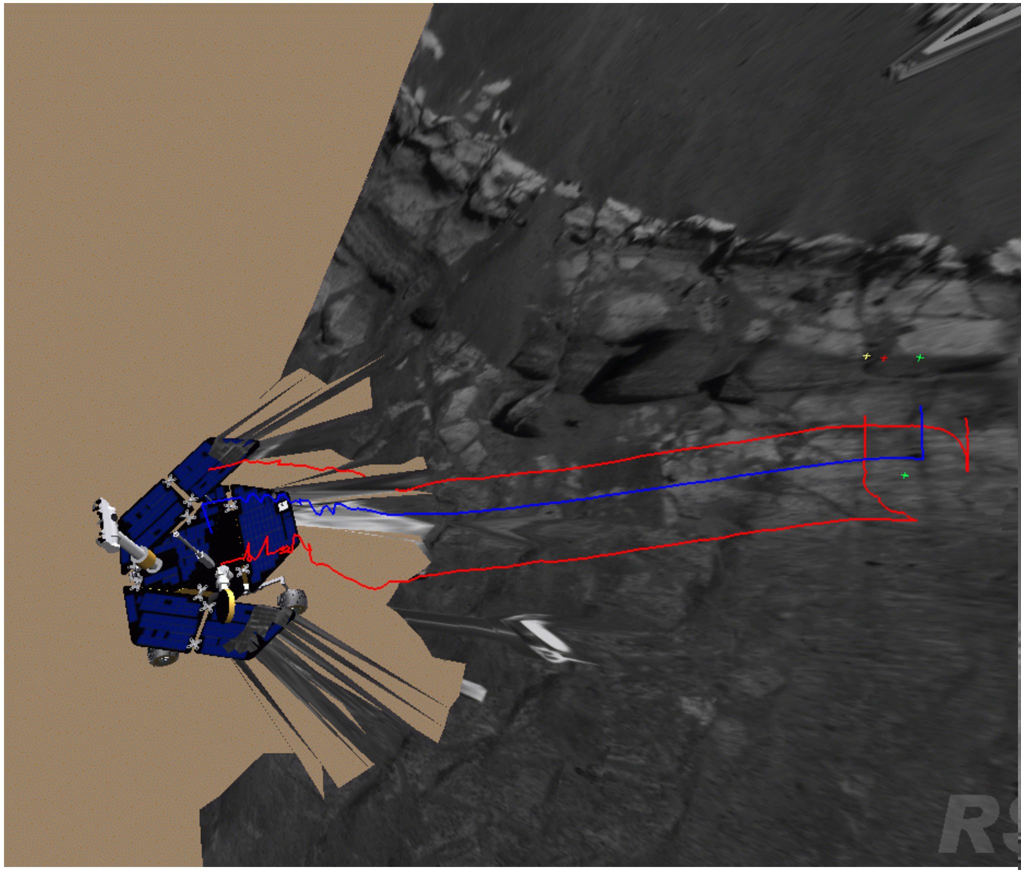
http://marsrover.nasa.gov/gallery/video/animation.html

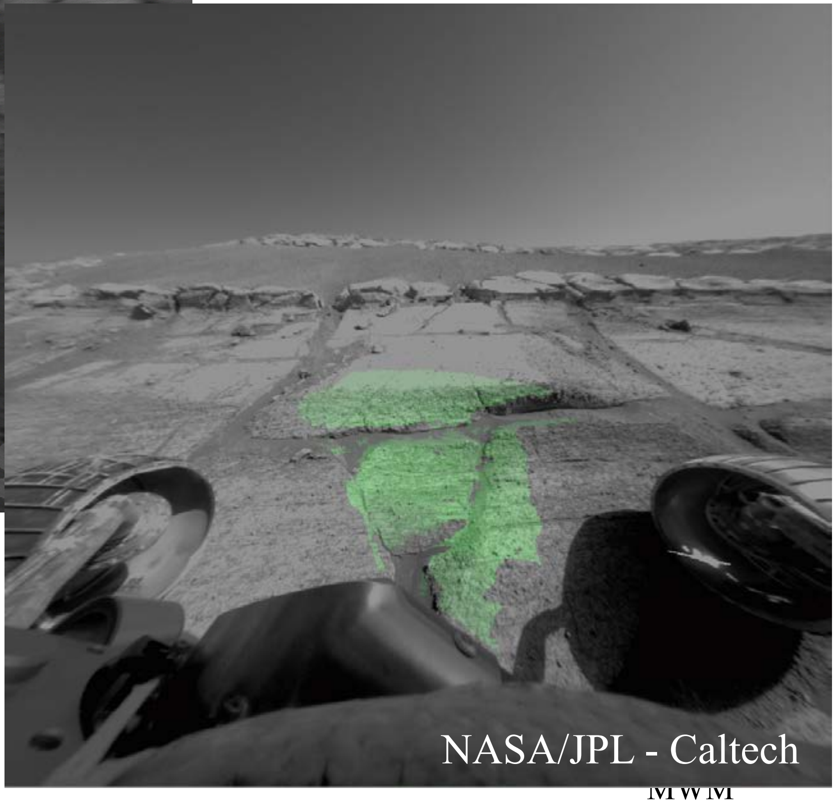
Visual Odometry Processing



- **VisOdom enables precise position estimates, even in the presence of slip, and enables Slip Checks and Keep-out zone reactive checks**

Science Return: Fewer Approach Sols

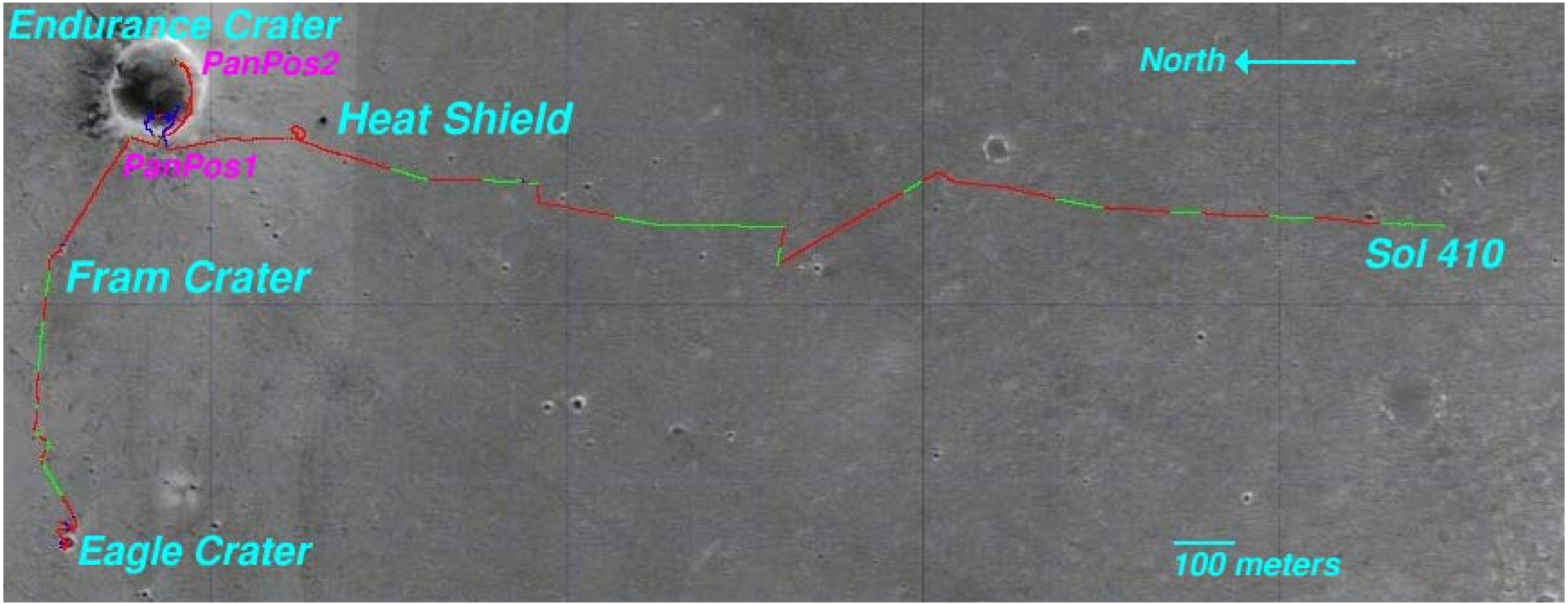




NASA/JPL - Caltech

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

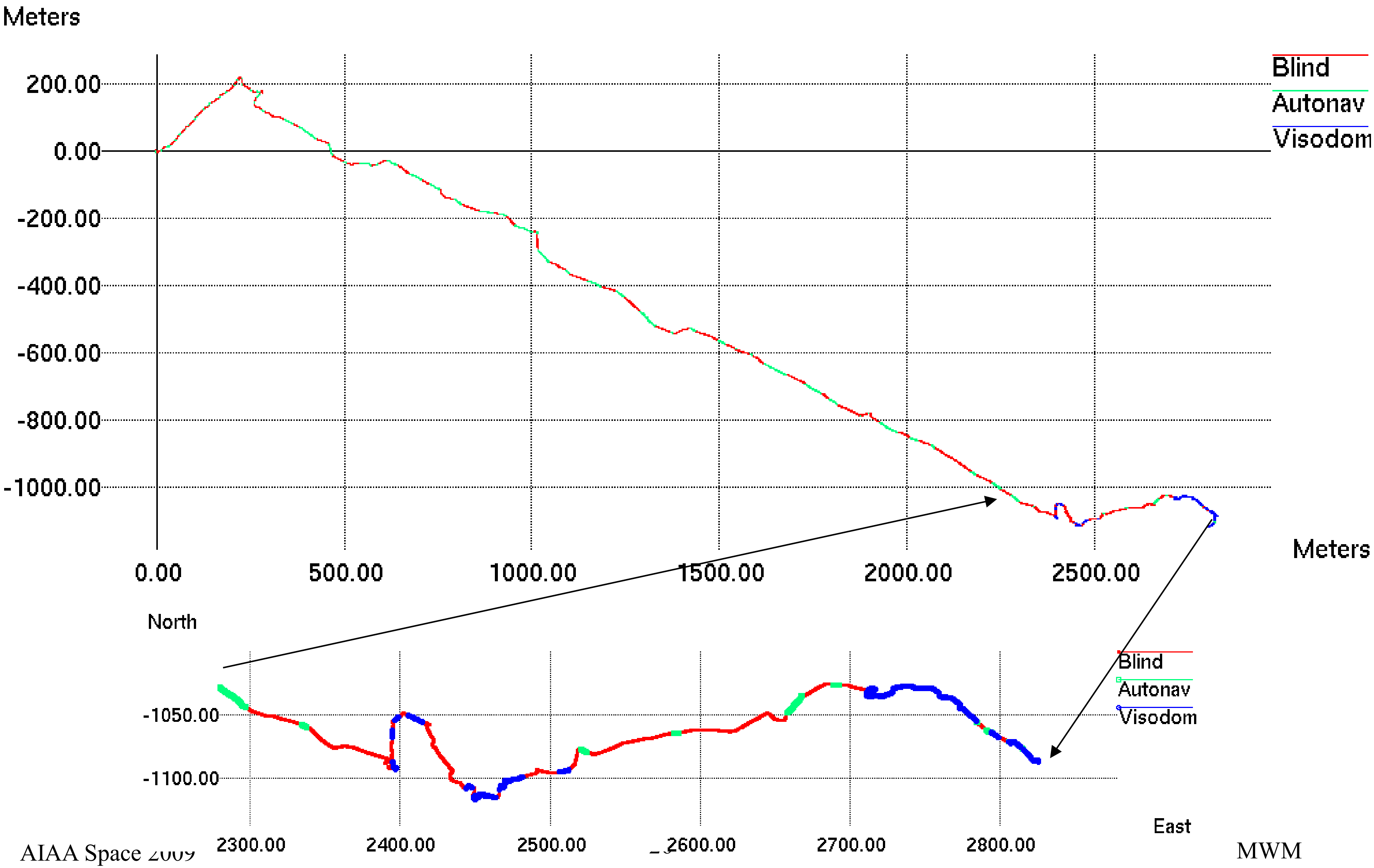
Opportunity Drive through Sol 410



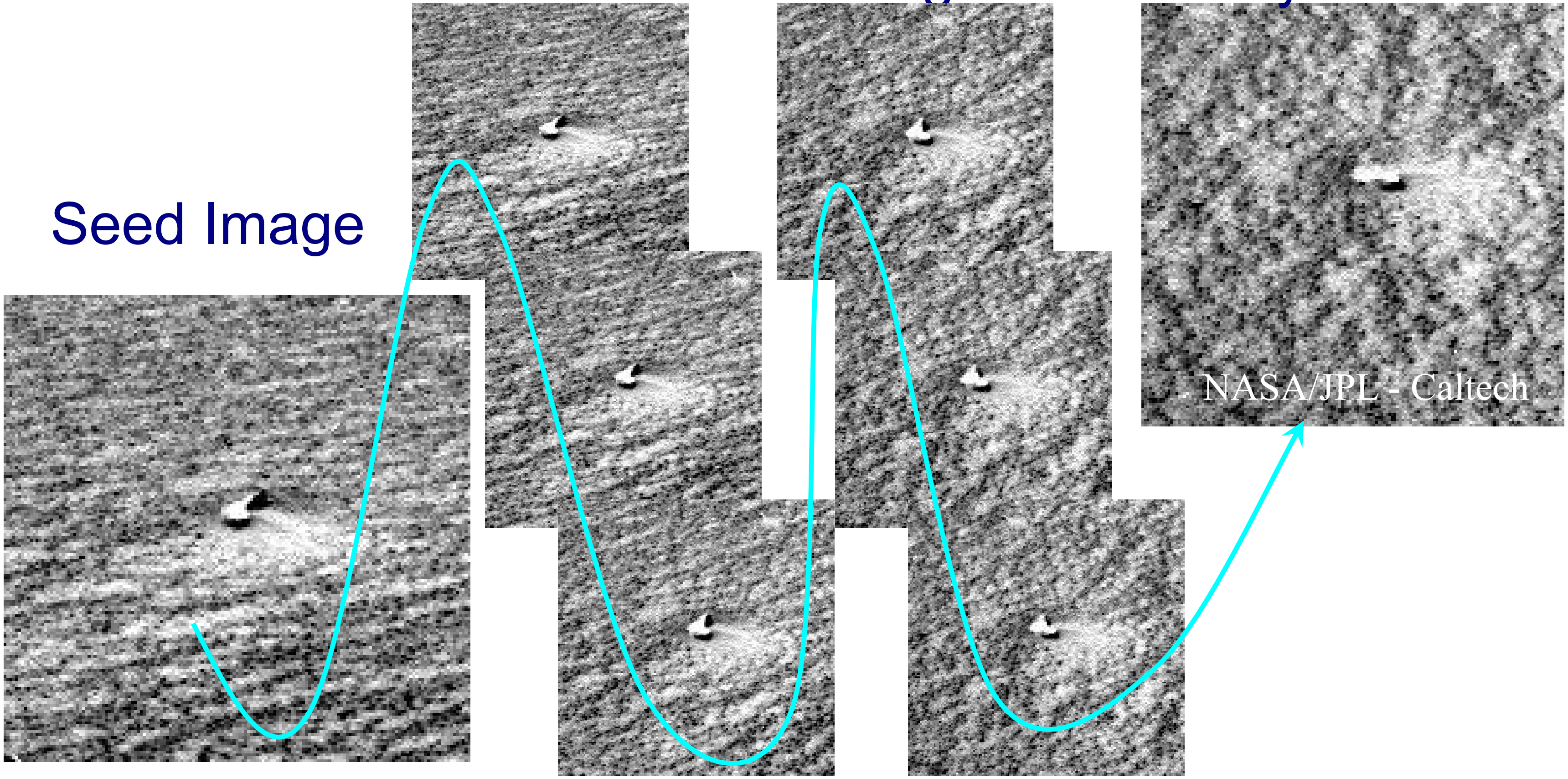
NASA/JPL/MSSS

Driving Modes:
Blind
Autonav
Visodom

Spirit Drive through Sol 418



Visual Terrain Tracking: B-992

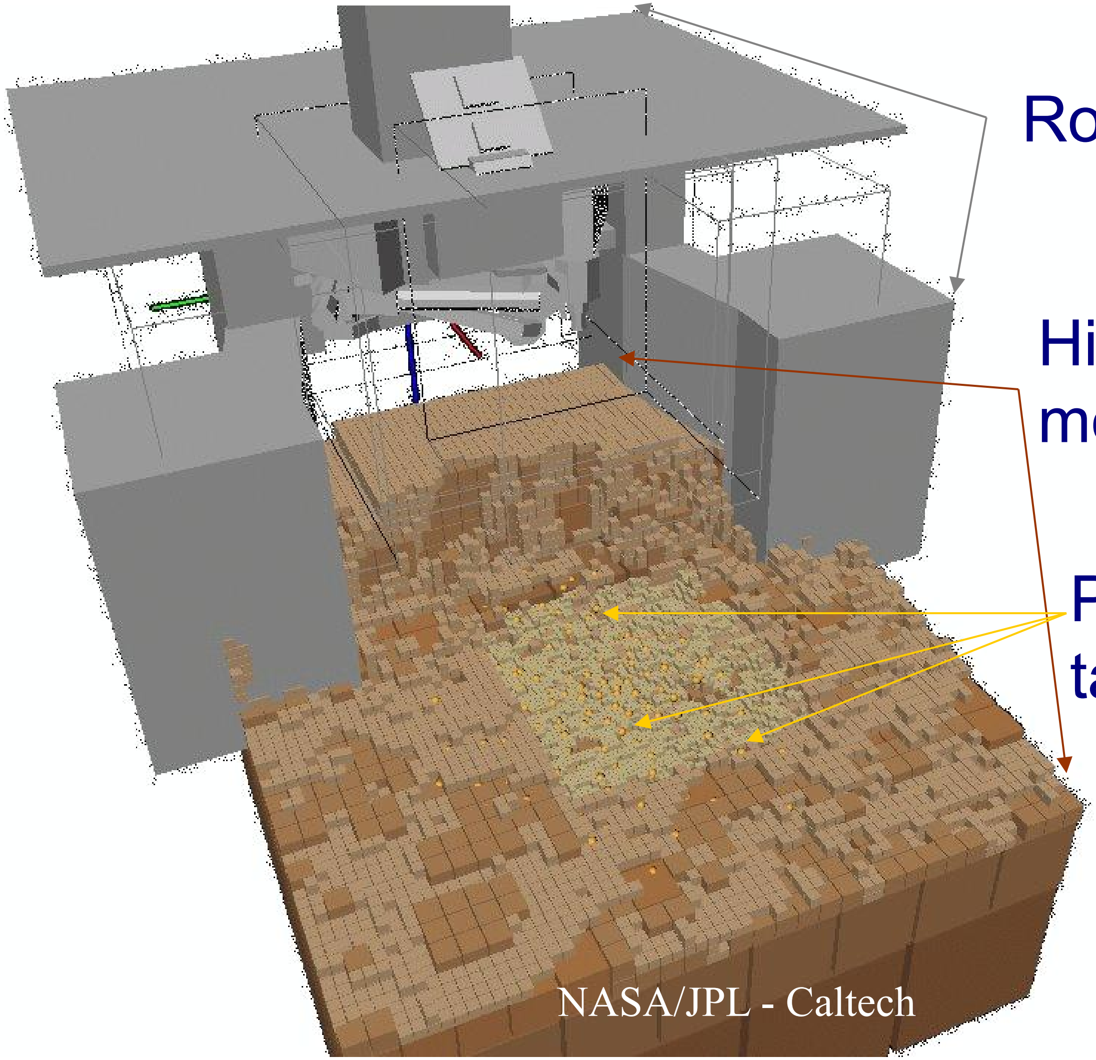


7 images and nearly 90° later…

Seed Image

NASA/JPL - Caltech

Instrument Arm Autoplace: A-1068



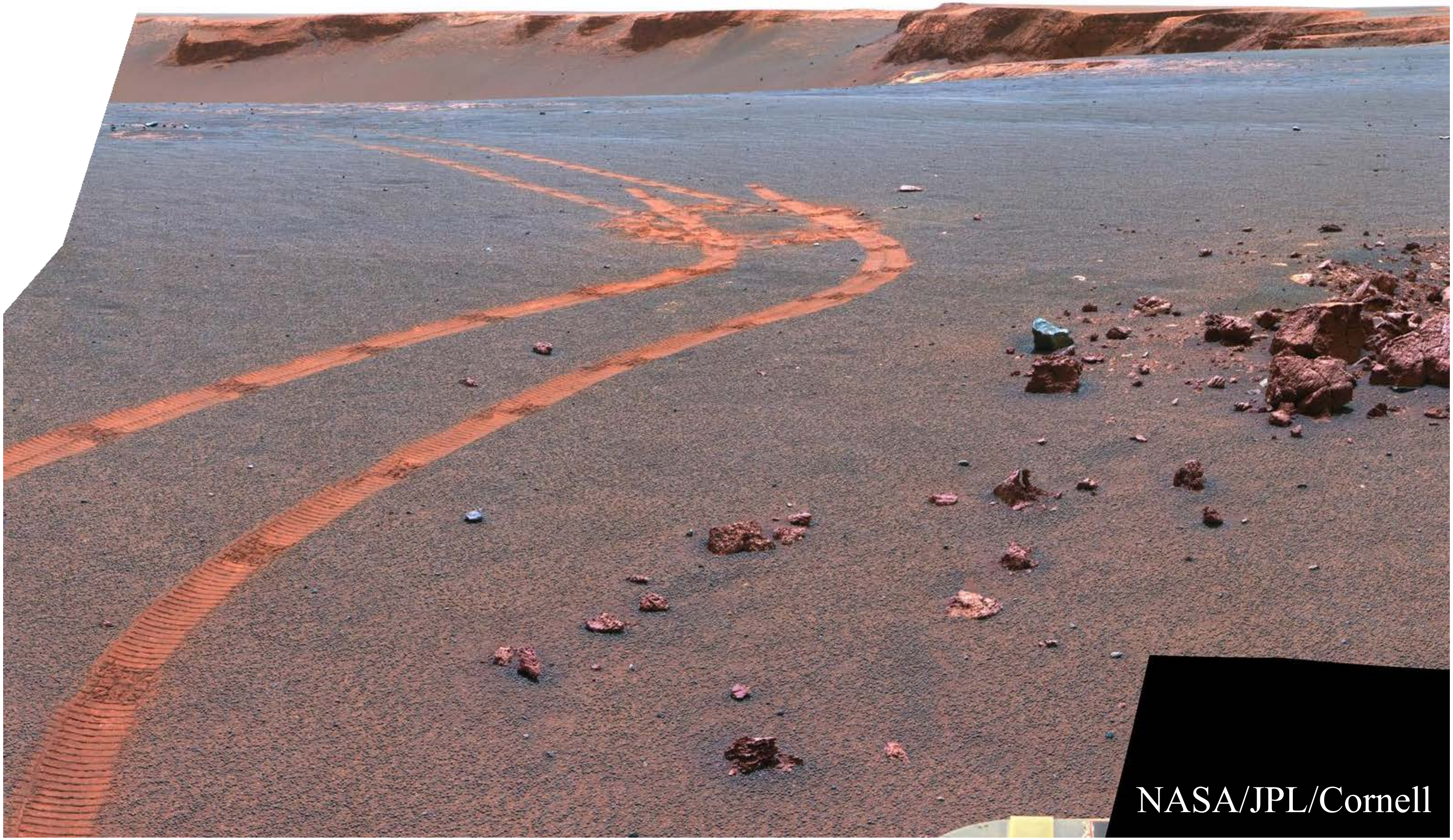
Rover Exclusion Zones

High resolution terrain model processed onboard

Potential IDD Placement targets

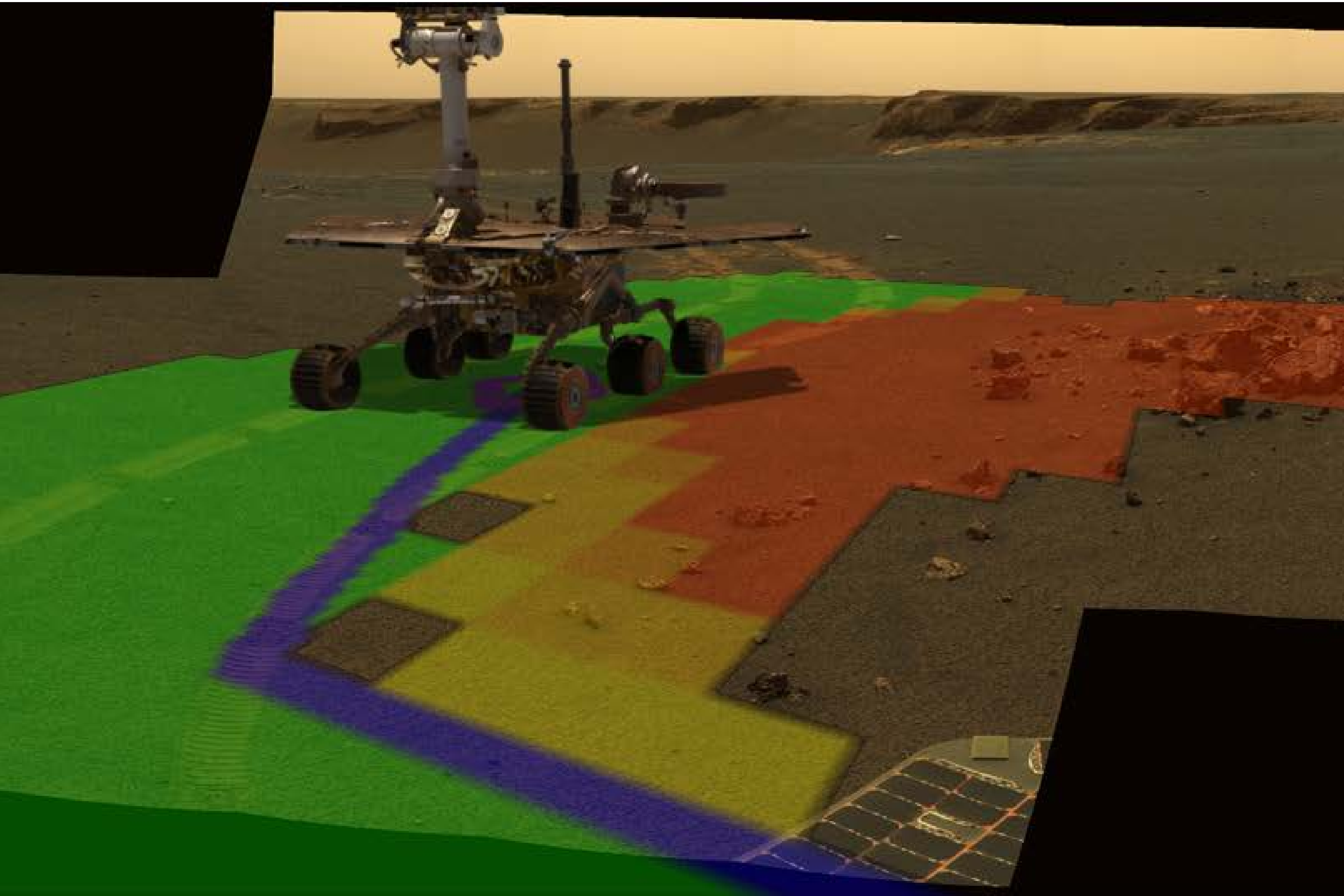
NASA/JPL - Caltech

Most MER Autonomy

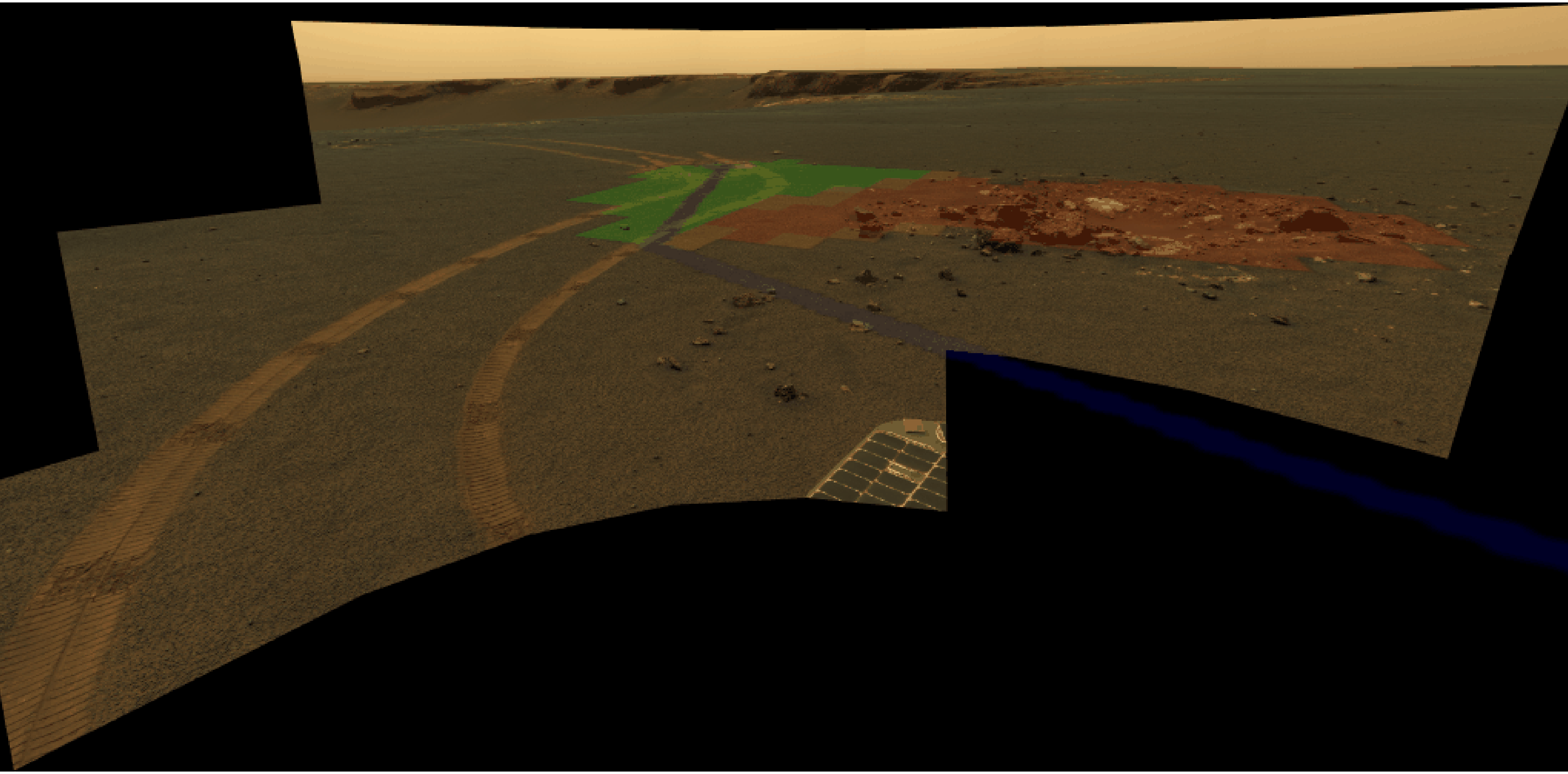


NASA/JPL/Cornell

Most MER Autonomy: Engineering Overlays

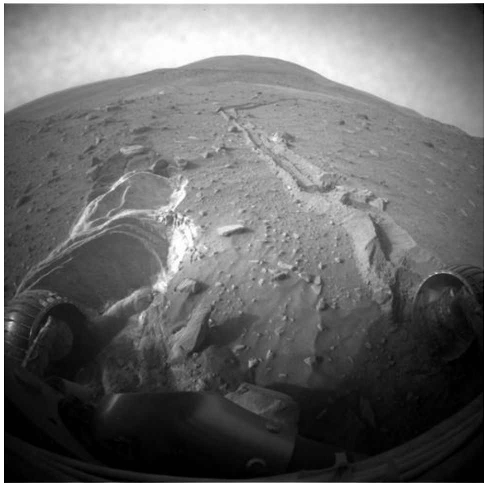


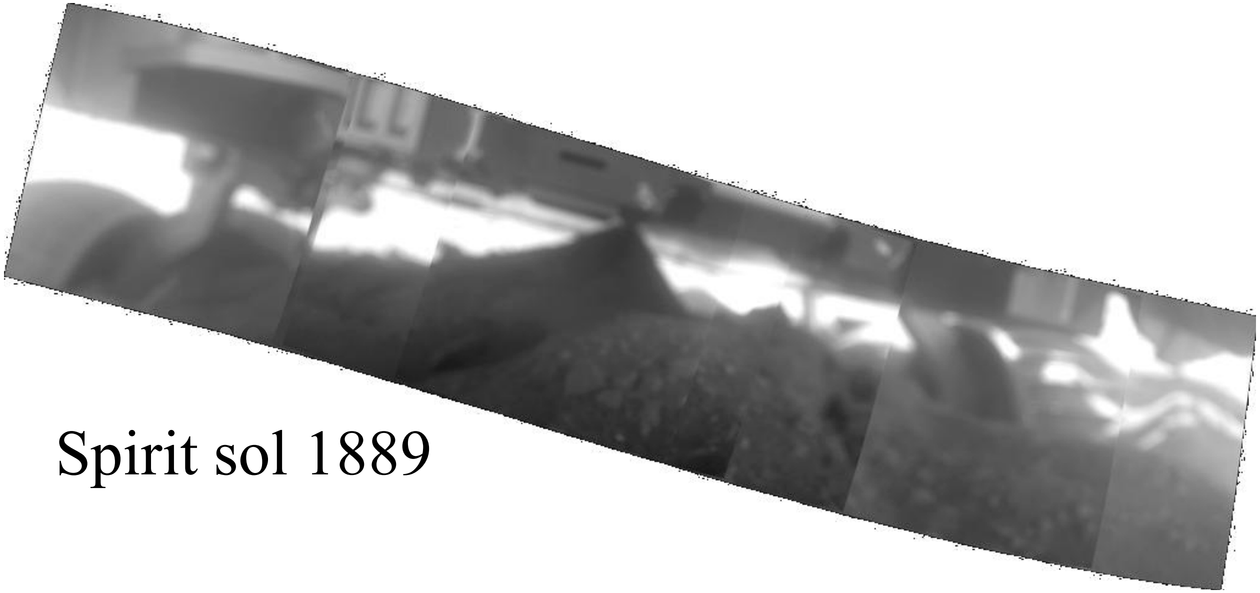
Most MER Autonomy: Overlay Animation



What Happens When Things Don’t Go As Planned?

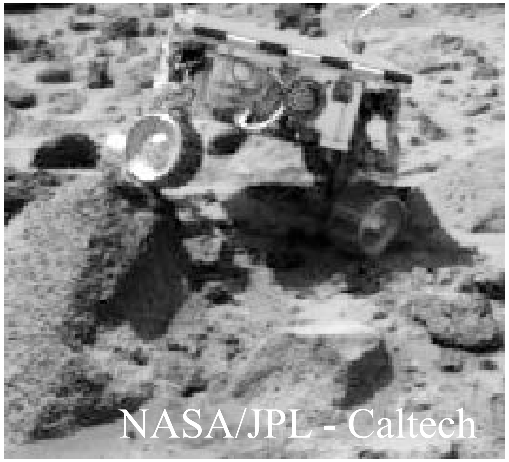
Operations: Expect the Unexpected



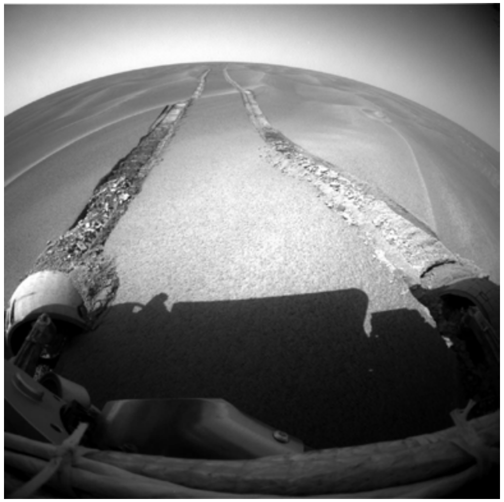


Spirit sol 1889

Sojourner sol 47



NASA/JPL - Caltech



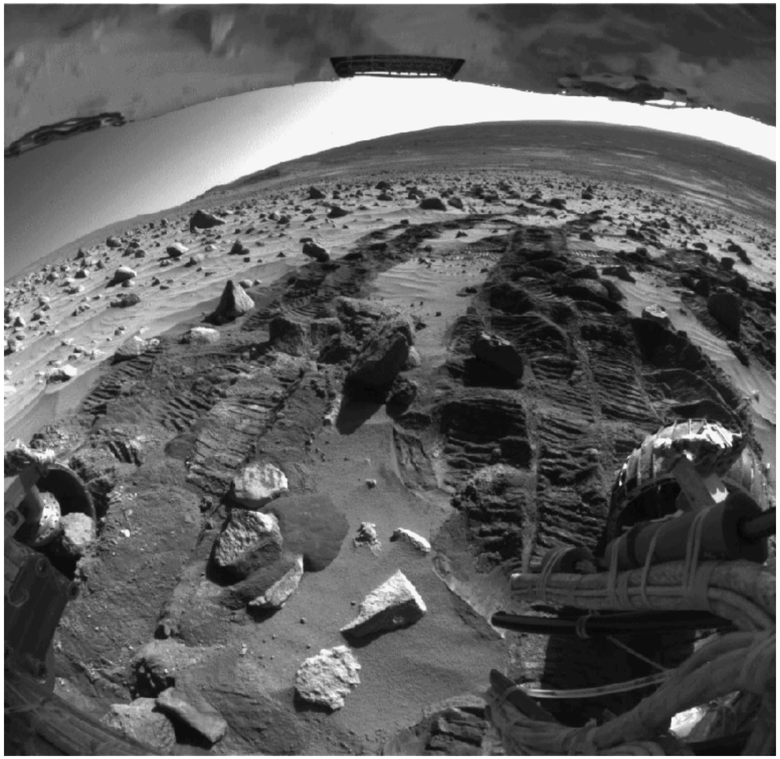
Opportunity sol 446

Lessons Learned: Opportunity Slip Check

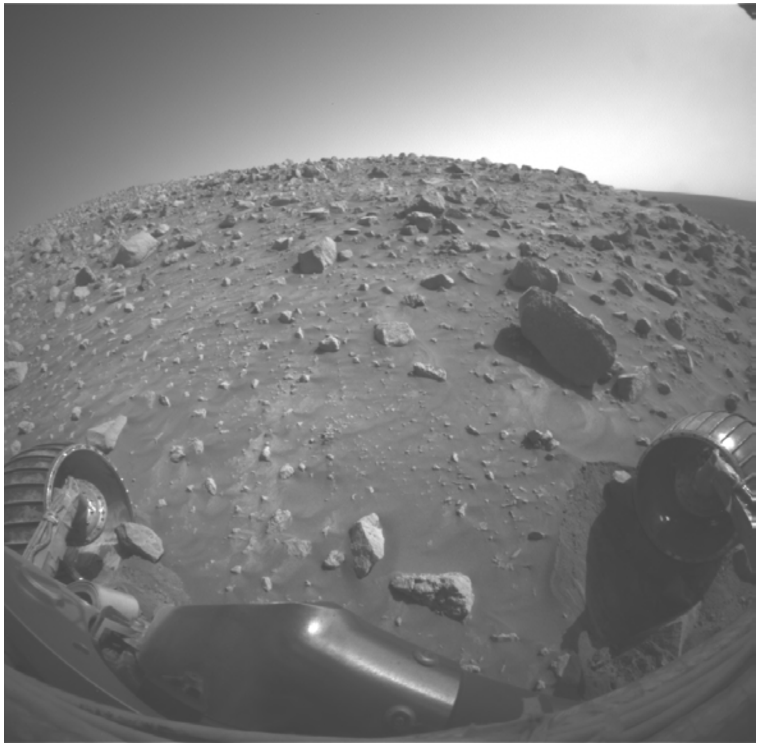
On B-446, 50 meters of blind driving made only 2 meters progress, burying the wheels. Recovery time: 5 weeks.

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

Lessons Learned: Spirit Slip Check



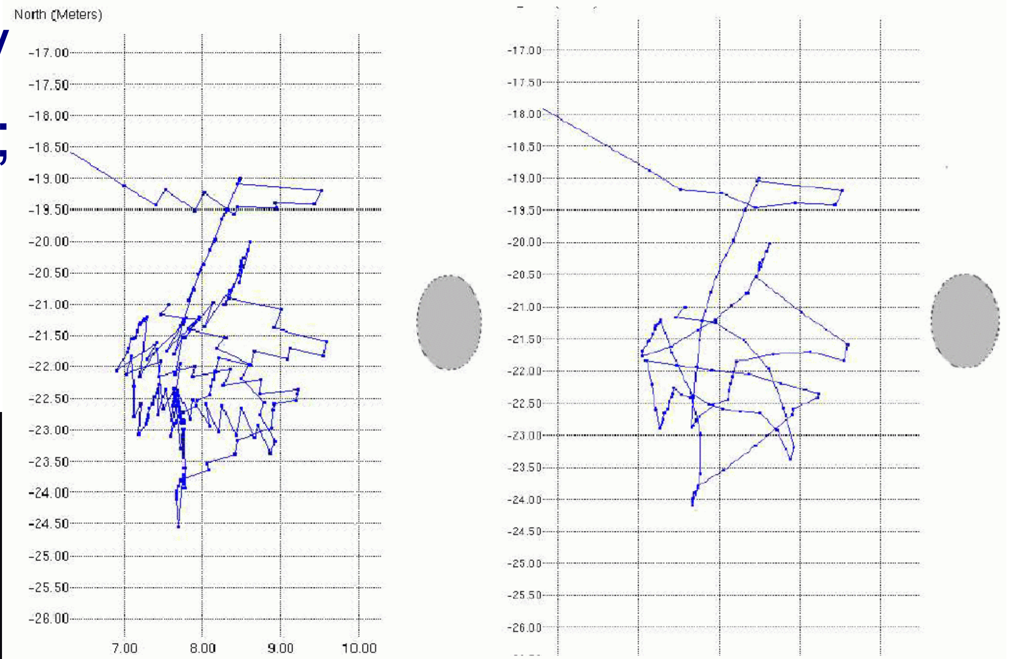
On A-345, Spirit stalled because a potato-sized rock had gotten wedged inside a wheel. Recovery time: 1 week.

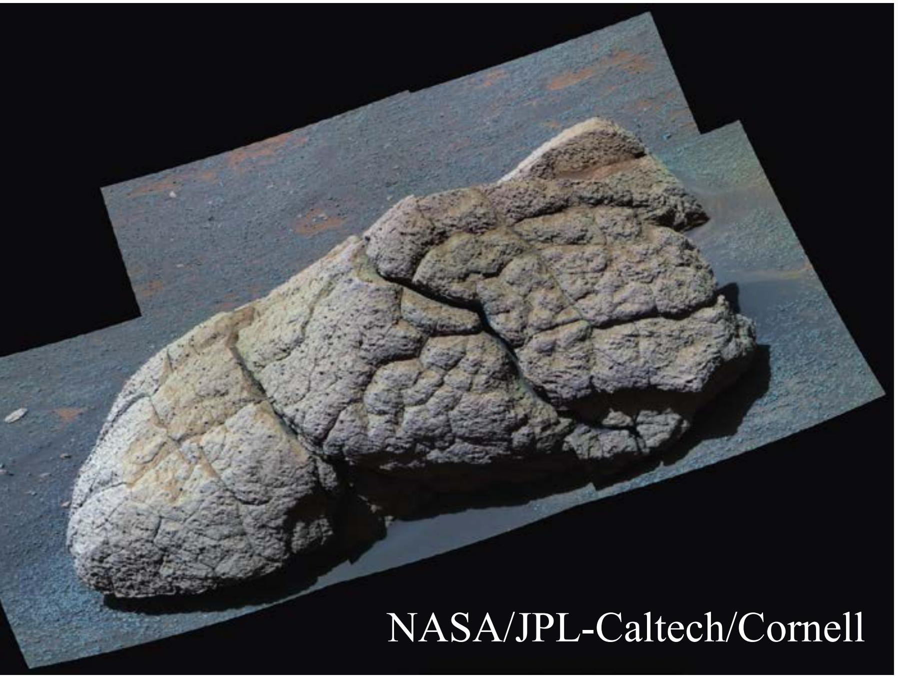


On A-454, Spirit detected 90% slip and stopped with rocks poised to enter the wheel. Recovery time: 1 day.

Ensuring Vehicle Safety: Keep-out Zones

From Sol 249-265, Opportunity kept sliding back into Wopmay; high slip, buried rocks, not enough uphill progress





NASA/JPL-Caltech/Cornell

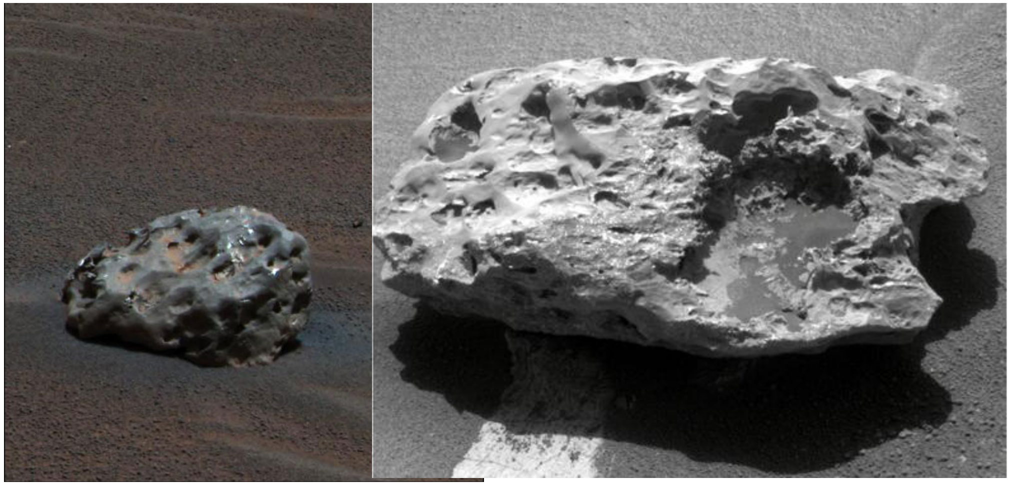
Each time VisOdom noticed the failure to make progress and prevented driving into it.

Spirit Settles at Hillary on Sol A-625

NASA/JPL - Caltech

Science Results: Expect the Unexpected

Spirit sol 1187 - dead drive motor uncovers silica-rich soil



Opportunity sol 339 - first iron meteorite found on another planet

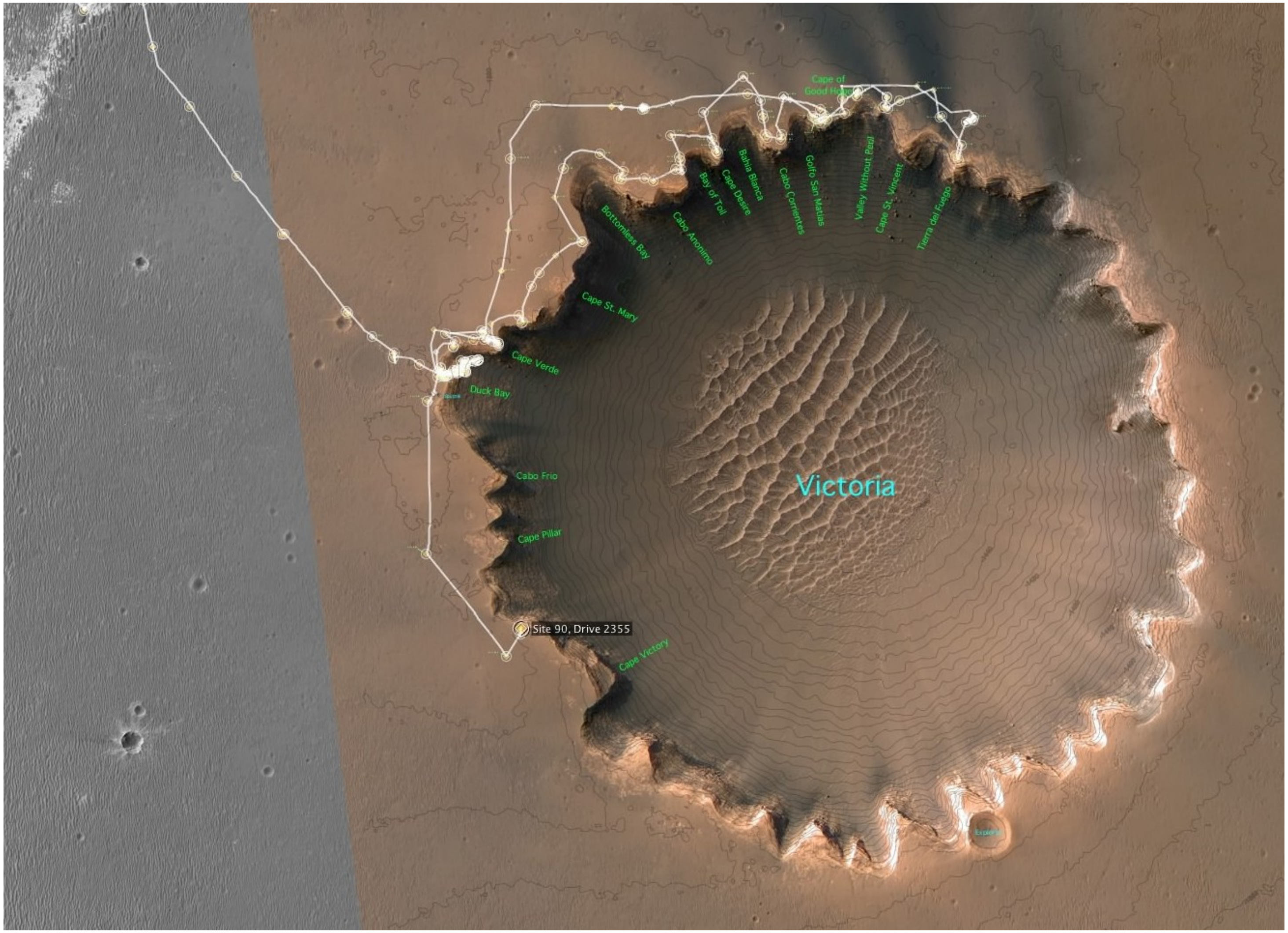
Opportunity sol 1961 - Iron-Nickel meteorite “Block Island”

The research described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

BACKUP SLIDES

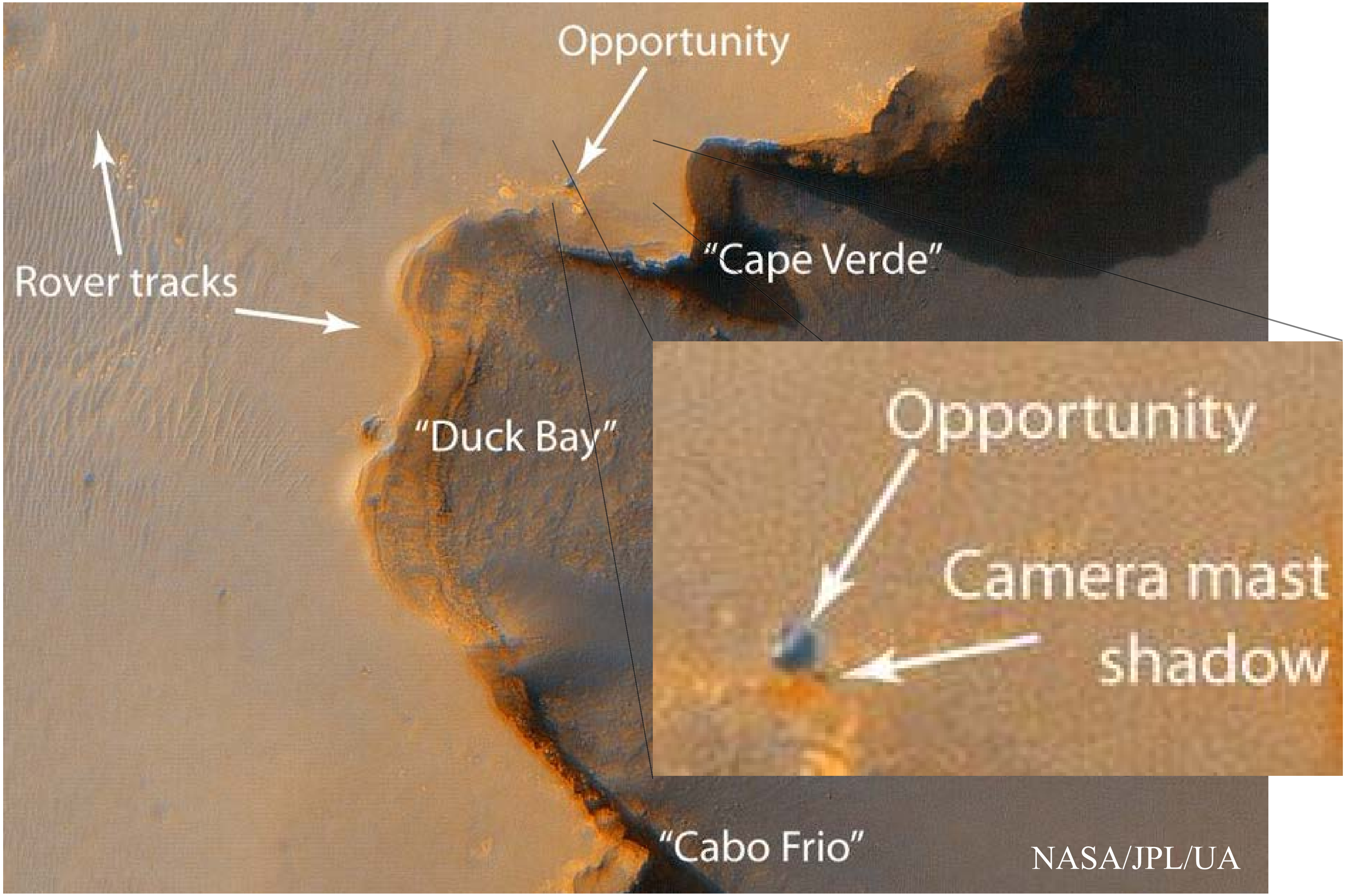
MER Explores Victoria Crater

Opportunity Traverse Around Victoria



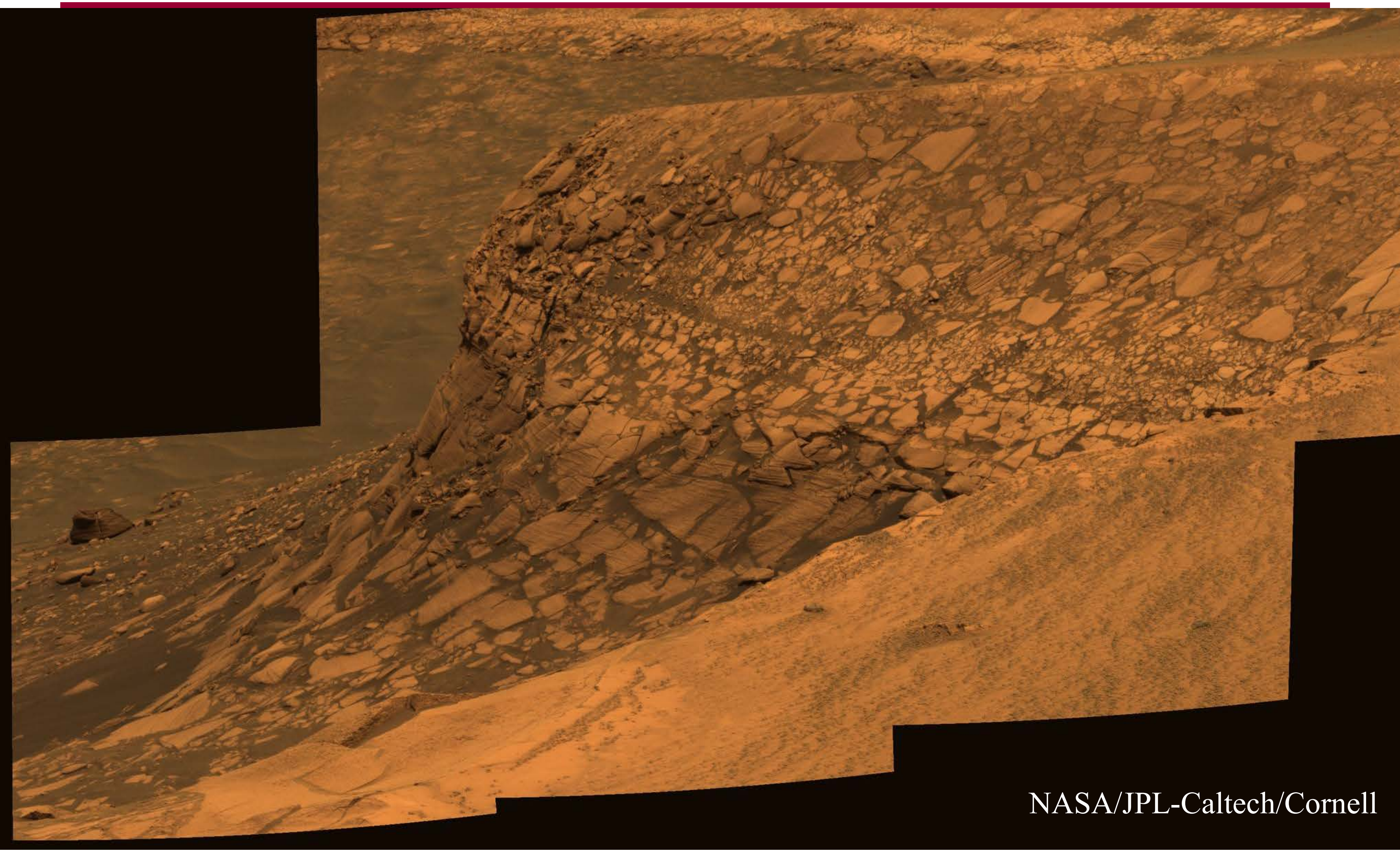
Sol B-1672 http://marsrovers.nasa.gov/mission/tm-opportunity-all.html

Opportunity Seen from Orbit



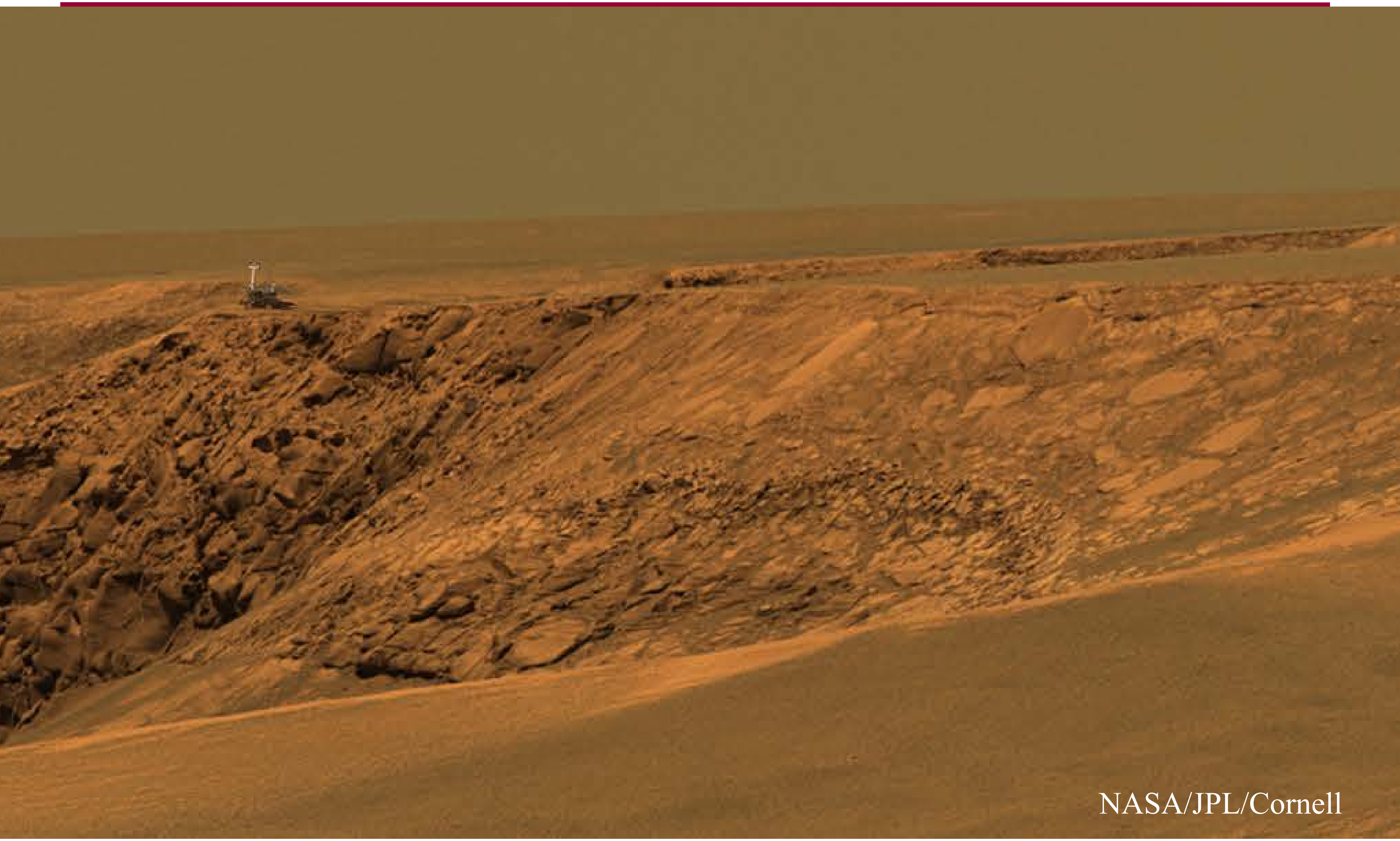
NASA/JPL/UA

Opportunity Views Cape Verde B-1006



NASA/JPL-Caltech/Cornell

Special Effects: Opportunity on Cabo Frio

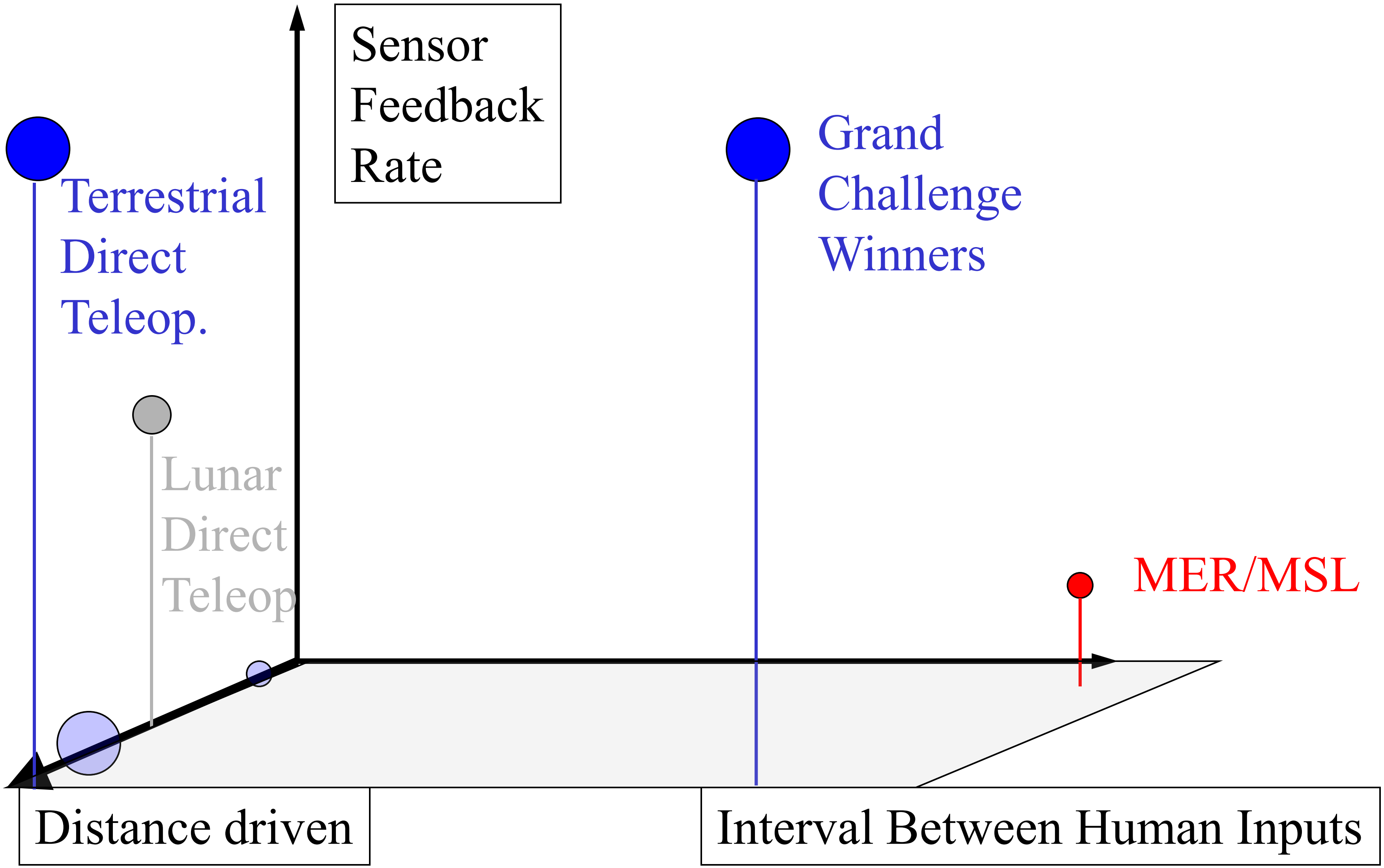


NASA/JPL/Cornell

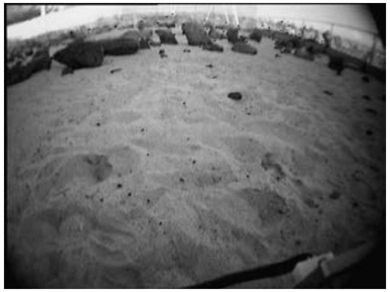
Special Effects: Opportunity at Victoria

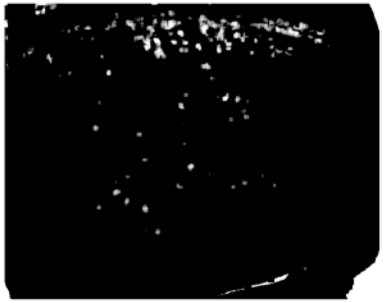
NASA/JPL/Cornell

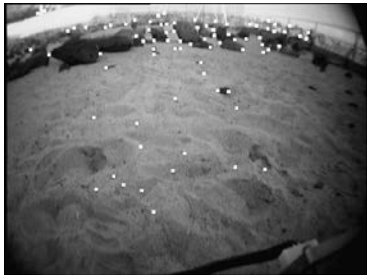
Mobility Autonomy Design Space

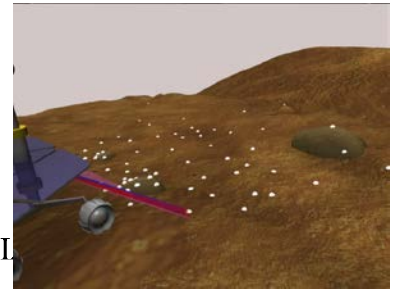


Visual Odometry Processing









- **Adjacent pairs of stereo images are processed onboard the rover**
- **Candidate features are selected and tracked automatically from one pair to the next**
- **Misleading or poorly matched features are automatically eliminated from consideration**
- **A 3-D motion estimate is generated from dozens of pairs of matched features**
- **This motion estimate replaces the previous best guess (derived from wheel odometry only) and can be used for precision pointing or driving, even when the wheels slip on sloped and/or loose terrain**

Style of Commanding

- **Direct teleoperation does not work (except on the Moon)**
  - Typically only one chance to send commands each day
  - Send a series of conditional, event-driven commands
- **Goal designation is different:**
  - On Earth, a goal might be set using a live beacon, or GPS coordinates
- **Planetary rover Goal designation has multiple error sources:**
  - Target specification error: locating the rover with respect to the goal at its initial position
    - Stereo range resolution dominates in rover-taken images, initial rover localization and map projection resolution dominate in infrequently-taken orbital images
  - Ensuring the proper goal has been reached at the end
    - Must either track the goal or carefully update rover position estimates along the way

Fault Responses

- **There is no kill switch**
  - The rover has to be programmed to be more conservative
- **Some faults are worse than others**
  - Surface operations are different than cruise operations
  - Fault behavior can be tailored to the current terrain
- **The command language needs to be designed to allow autonomous fault detection and recovery**
  - Must allow the system to be retuned for different types of terrain; we don't have smart enough sensing to autonomously switch behaviours based on terrain yet
  - Adding contingencies into the plan for benign or expected faults will improve overall mission return
- **Plan for degraded operations when components fail**

MER Design due to Environment and KISS

- **Low power: Nominal mission planned to succeed even with limited power**
- **Slow driving: Wheel motor gear ratios were determined by the needs of worst-case climbing**
  - So it can climb over obstacles, but its top speed is limited even in benign terrains
- **Limited sensing**
  - No camera can see the middle wheels or under the rover
  - A small number of cameras was chosen to minimize the power required and system integration complexity

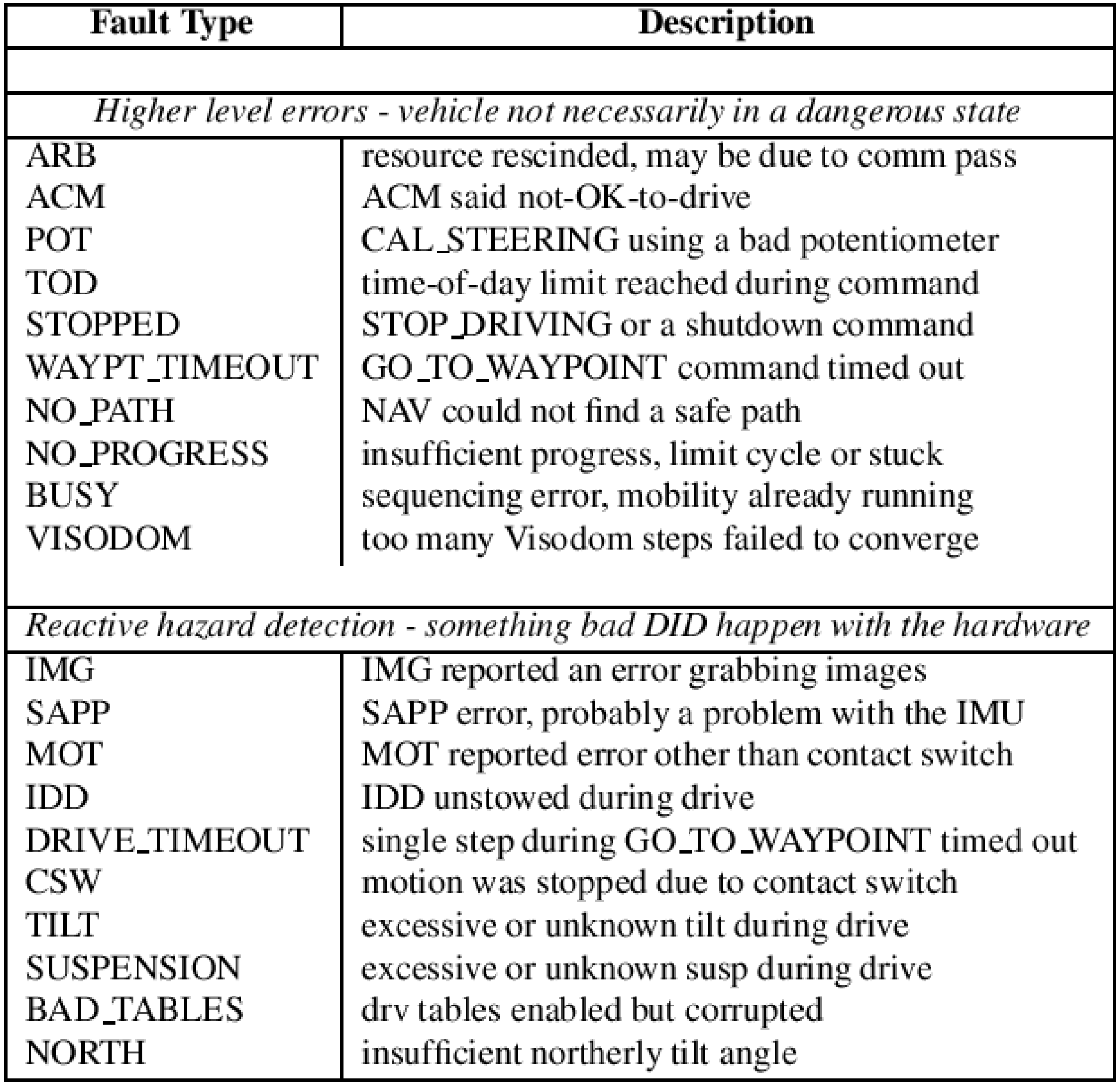
MER Style of Commanding

- **A series of event-driven conditional commands is updated each drive day**
- **Drive goals are normally specified using X,Y,Z**
  - Short range drive goals (< 20 m) from onboard Navcam range data
  - Long range drive goals from Pancam range data or orbital images
- **Only goals that allow for accumulated position estimation error are selected**
  - Position error can be minimized by enabling Visual Odometry
- **Visual Target Tracking can eliminate target specification error**
  - Constantly re-estimating target location visually during a drive

MER Fault Responses

- **Two classes of driving faults: Goal and Motion Errors**
  - Goal Errors simply indicate the planned location wasn't achieved; the vehicle is still safe
  - Motion Errors indicate some system parameter is out of range, e.g., motor current, vehicle tilt
    - But ranges are selected to ensure overall vehicle safety; even if "out of range", you can still have sufficient power and communications
- **Command sequences can behave conditionally on fault type**
  - The more time you have, the more alternatives you can plan for
- **Unplanned faults leave the vehicle in a safe state**
- **Both MER vehicles are dealing with failed motors, yet continue to perform useful science**

MER Mobility Faults

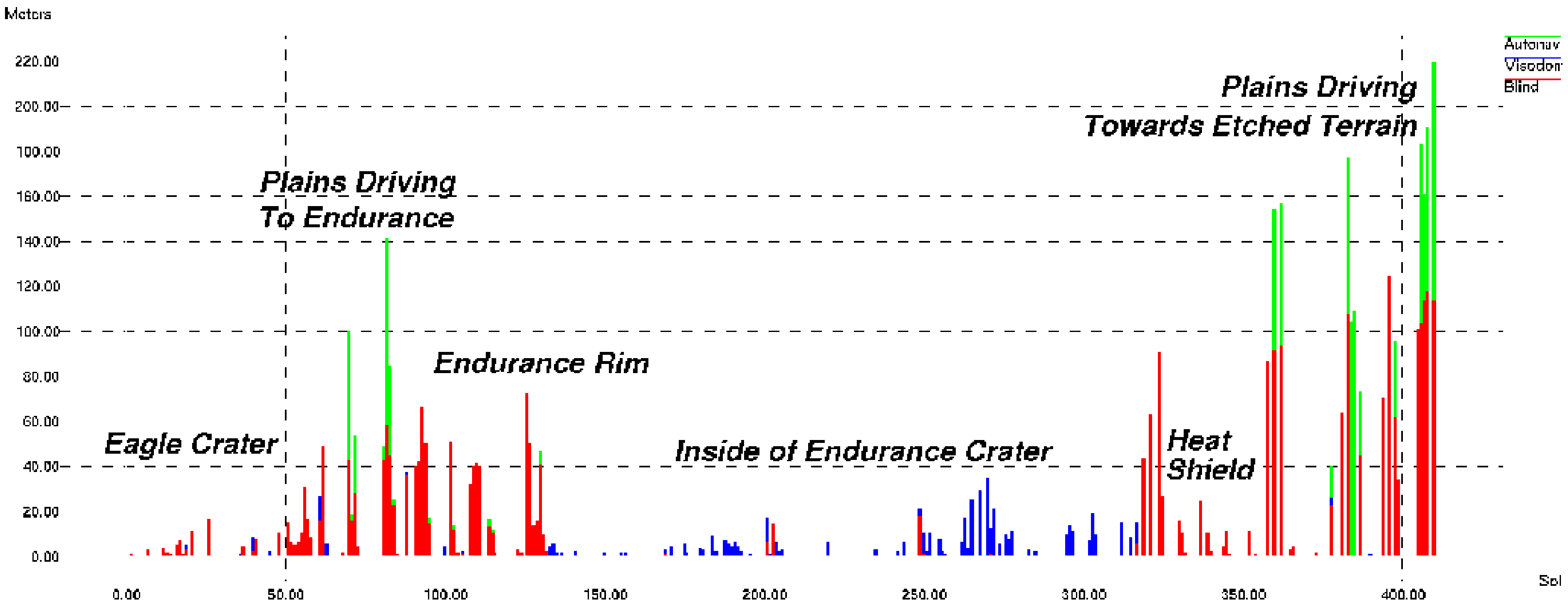


Fault Type	Description
Higher level errors - vehicle not necessarily in a dangerous state	
ARB	resource rescinded, may be due to comm pass
ACM	ACM said not-OK-to-drive
POT	CAL_STEERING using a bad potentiometer
TOD	time-of-day limit reached during command
STOPPED	STOP_DRIVING or a shutdown command
WAYPT_TIMEOUT	GO_TO_WAYPOINT command timed out
NO_PATH	NAV could not find a safe path
NO_PROGRESS	insufficient progress, limit cycle or stuck
BUSY	sequencing error, mobility already running
VISODOM	too many Visodom steps failed to converge
Reactive hazard detection - something bad DID happen with the hardware	
IMG	IMG reported an error grabbing images
SAPP	SAPP error, probably a problem with the IMU
MOT	MOT reported error other than contact switch
IDD	IDD unstowed during drive
DRIVE_TIMEOUT	single step during GO_TO_WAYPOINT timed out
CSW	motion was stopped due to contact switch
TILT	excessive or unknown tilt during drive
SUSPENSION	excessive or unknown susp during drive
BAD_TABLES	drv tables enabled but corrupted
NORTH	insufficient northerly tilt angle

Resource Modeling

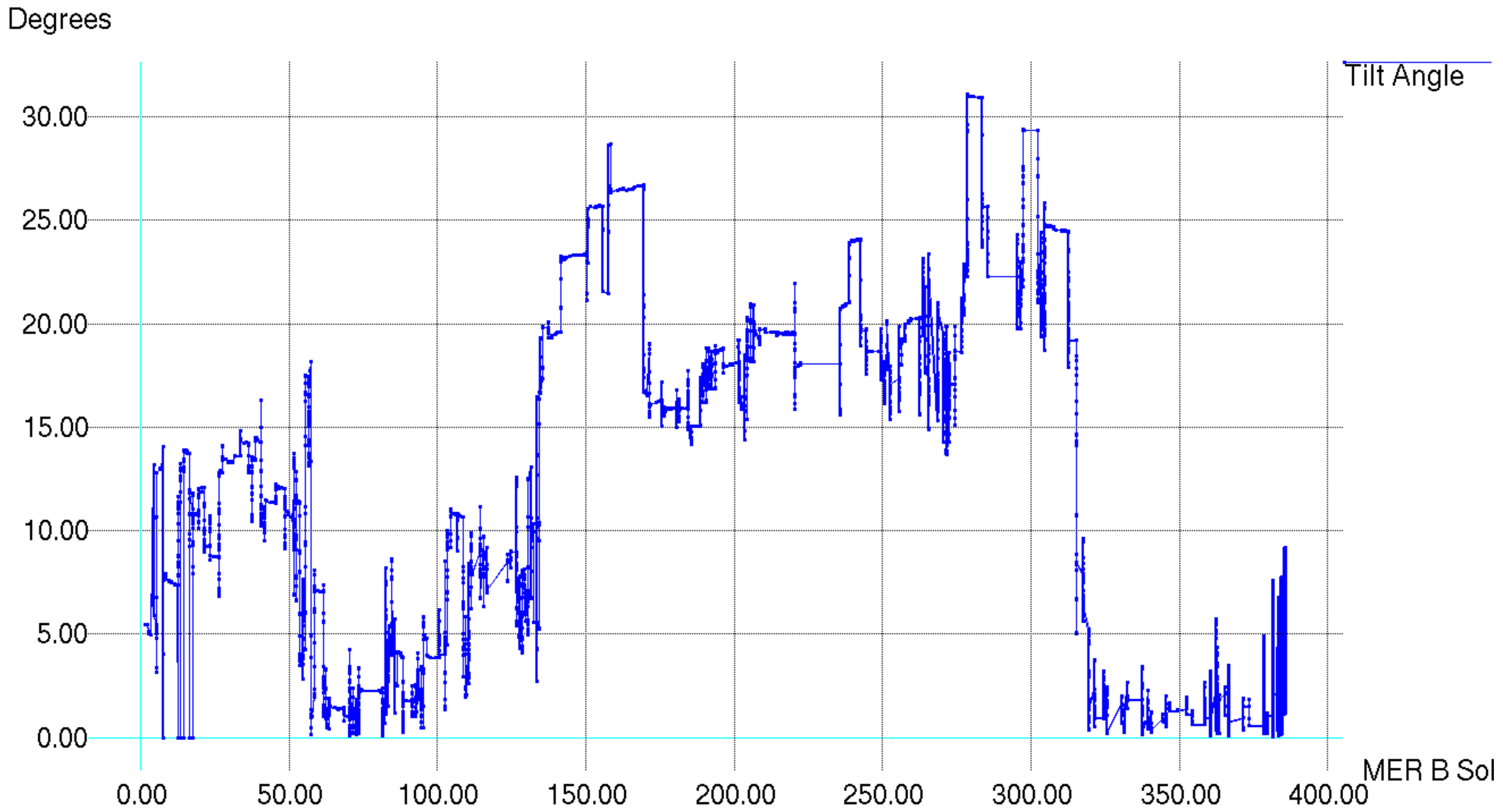
- **Any autonomy technology transitioning to flight must include a prediction of its CPU resource use as a function of sensed data size (e.g., image resolution)**
  - RAM, CPU time
- **Rover operations team will need to model overall system resource use during each day:**
  - Power
  - Time required
  - Data Volume

Opportunity Drive Modes in first 410 Sols



Data from rover's onboard position estimate

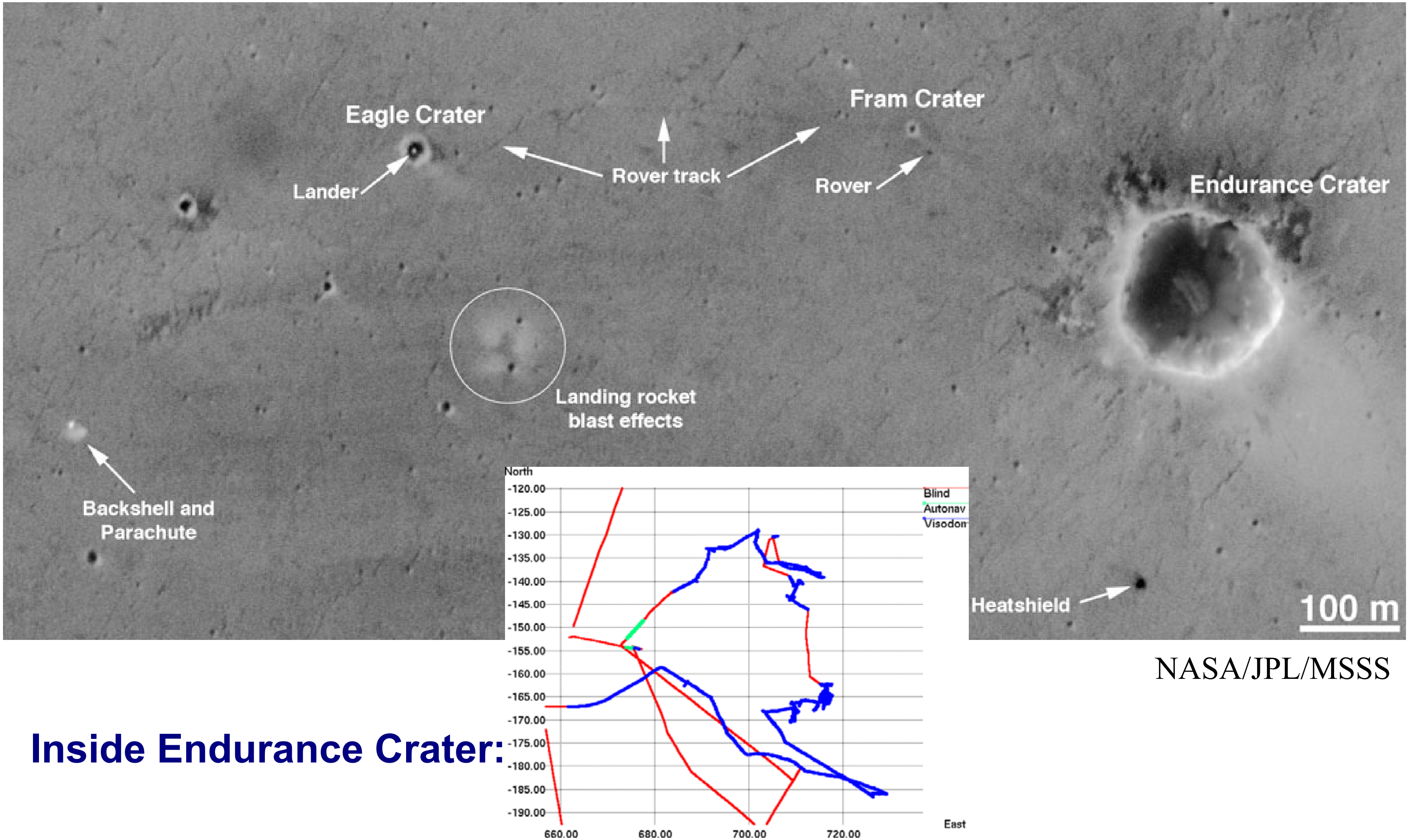
Opportunity Tilt History through Sol 380



Conclusion

- **Planetary robots can take advantage of many new robotic technologies**
  - But only if they are tailored to the mission constraints
- **Faster processors would improve autonomy behavior, but not by orders of magnitude**
  - Mechanical and other sensor bottlenecks quickly come into play
- **More focus needed on reducing the number of days spent at a science feature**
  - Most time is spent performing in situ work at science targets, efficiency improvements there will have a large impact on overall mission science return

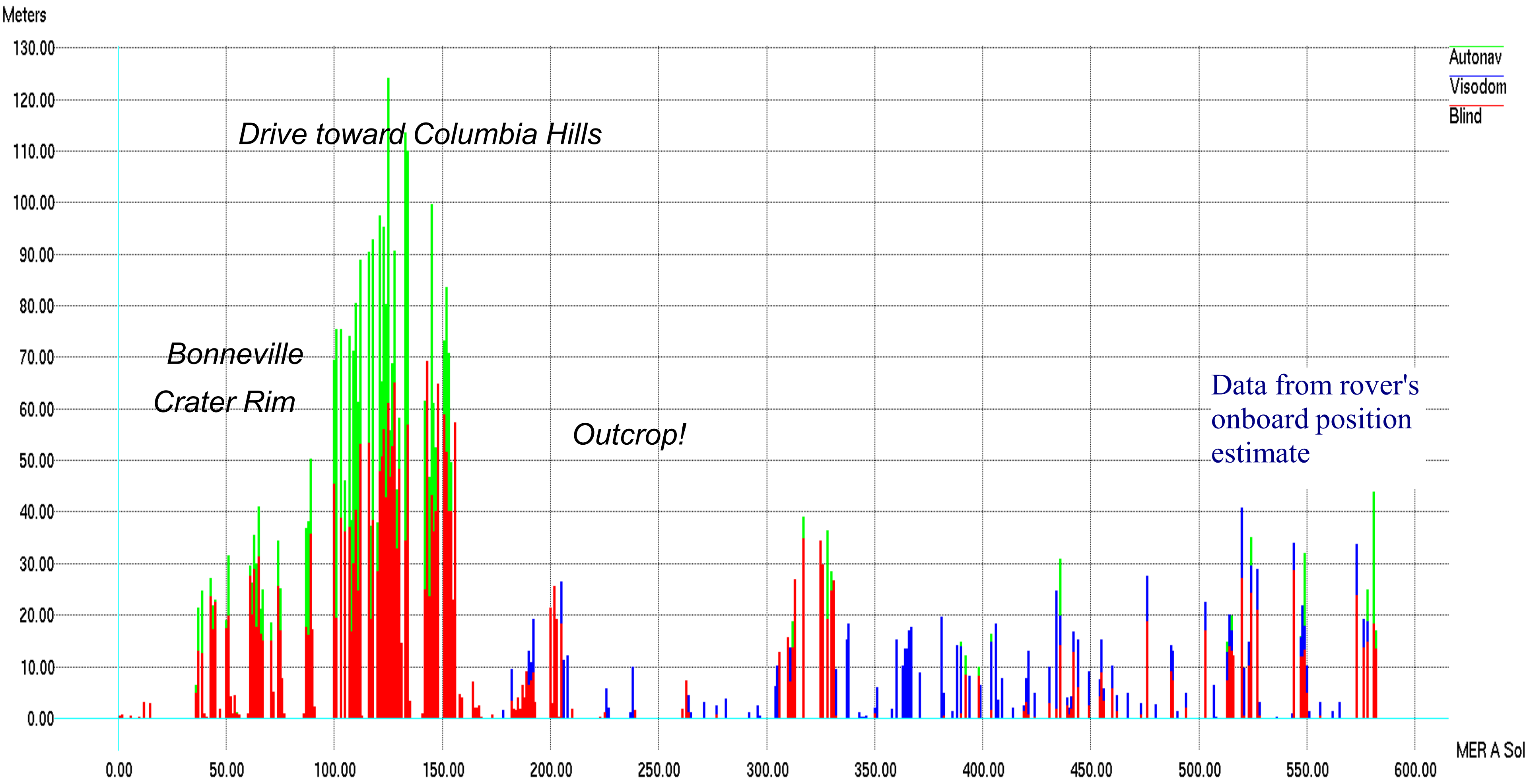
Opportunity Drive to Endurance Crater



Inside Endurance Crater:

NASA/JPL/MSSS

Spirit Drive History through Sol 588



Drive toward Columbia Hills

Bonneville

Crater Rim

Outcrop!

Data from rover's onboard position estimate

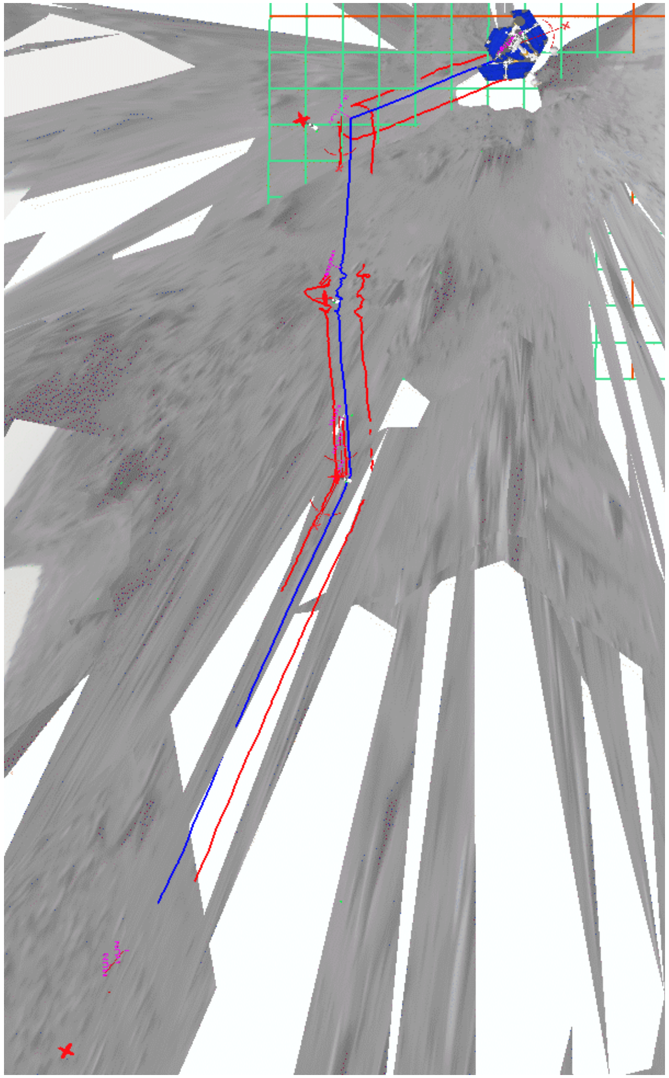
MER FSW 9.1 Drive Constraints

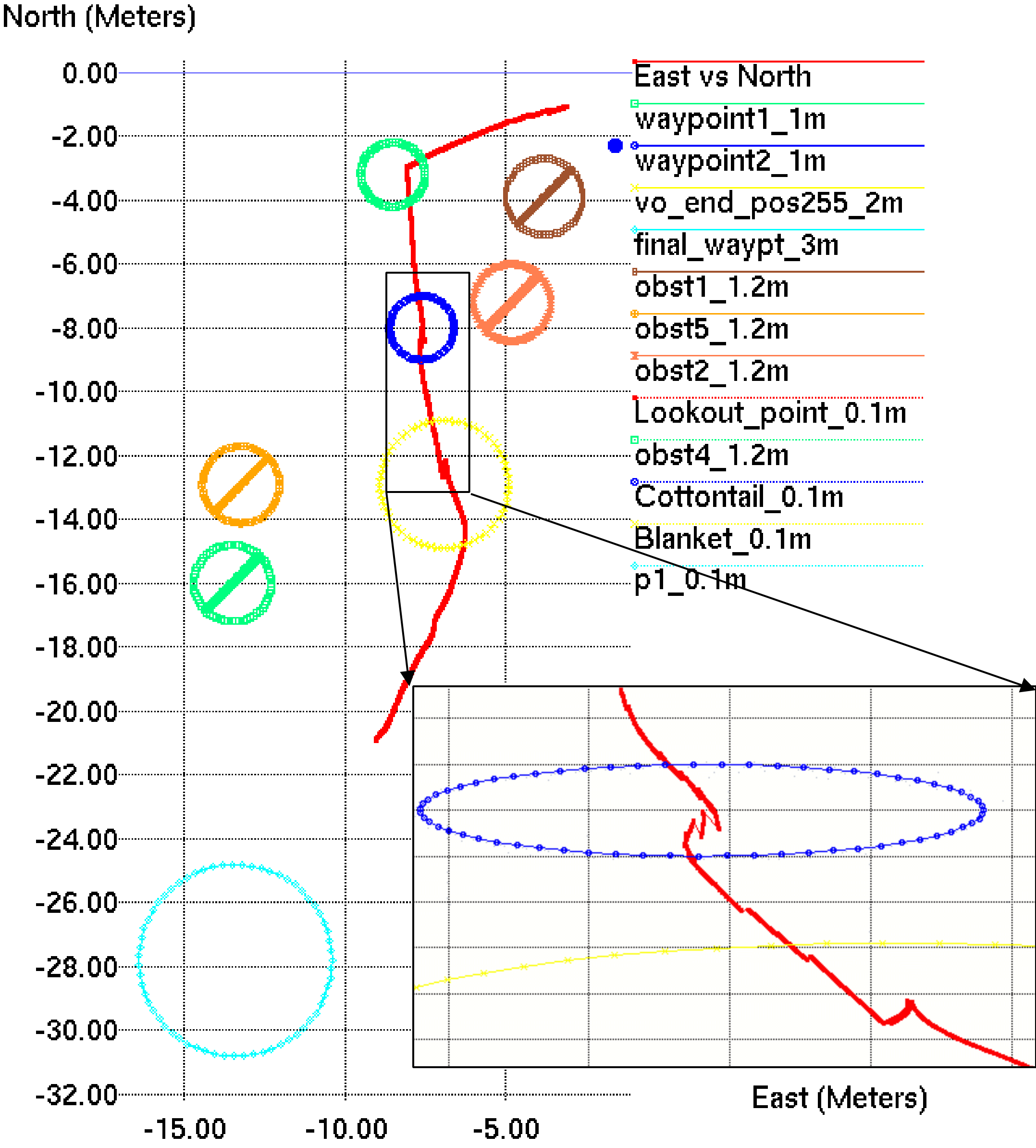
- Typically only enough power to drive 4 hours/day
- Rover generally sleeps from 1700 – 0900; humans plan next day's activities while it sleeps, e.g. human terrain assessment enables a blind drive
- A single VisOdom or AutoNav imaging step takes between 2 and 3 minutes (20MHz CPU, 90+ tasks)
- Onboard terrain analysis only performs geometric assessment; humans must decide when to use VisOdom instead of/in addition to AutoNav
- Placement of Arm requires O(10cm) precision vehicle positioning, often with heading constraint

A-436: Exercising 3 Drive Modes

- Here’s an example of a sol that used 3 drive moves
- The drive plan for Spirit's Sol 436 was:
  - **Back up 5m cross-slope**
  - **Drive upslope with VisOdom using 2 waypoints**
    - **Run Obstacle Check in parallel**
  - **Bear right and run AutoNav (no more VisOdom) to climb a reduced slope in unseen area**
- One last note says:
  - ***This avoids the 25deg slopes along the front ledge on the upslope***

Planned vs. Actual Drive: A-436





Visodom Benefits

- Visual Odometry has proven a highly effective tool for driving in high-slip areas
- Tangible benefits:
  - **Increased Science Return**
    - **Provided robust mid-drive pointing**
    - **Enabled difficult approaches to targets in fewer Sols**
  - **Improved Rover Safety**
    - **Keep-out zones**
    - **Slip checks**

Autonomy Tradeoffs

- Benefits:
  - **Adapts to current vehicle state**
  - **Can drive into unknown areas**
  - **Faster planning time**
- Disadvantages:
  - **Can be order of magnitude slower than Directed**
  - **VisOdom cameras need to be manually pointed**
  - **VisOdom-only mode needs manual Keep-out zones**
  - **Only geometric terrain classification; cannot predict high slip areas**
  - **Unknown use of resources and final state**

Directed Driving Tradeoffs

- Benefits:
  - **Fastest execution time**
  - **More “predictable” final state**
  - **Strategies may be adapted daily**
- Disadvantages:
  - **Can only drive as far as you can see**
  - **Needs much more planning effort**
  - **Limited terrain adaptability; yaw knowledge only**
  - **Cannot plan mid-drive precision imaging with slip**