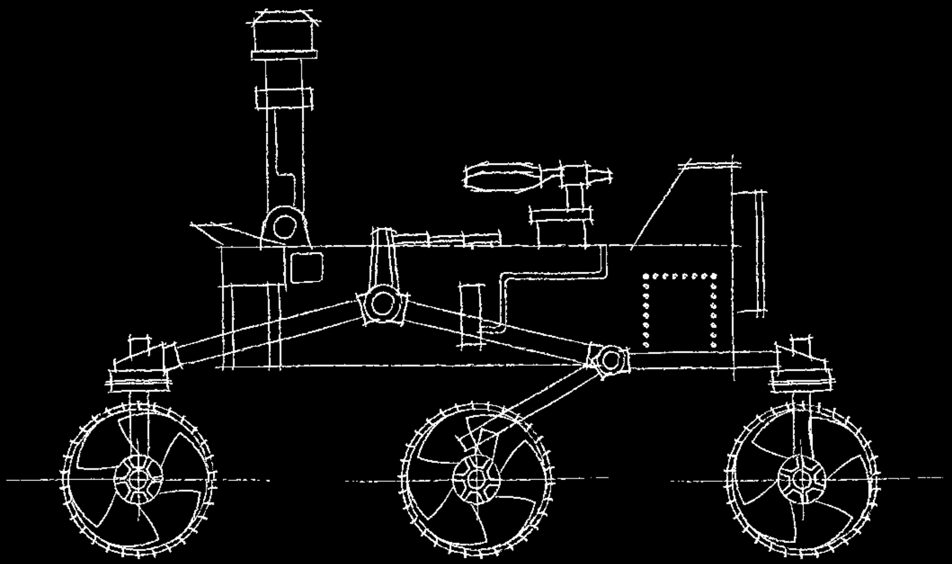
Jet Propulsion Laboratory
California Institute of Technology

AutoNavigation: Intuitive Autonomy on Mars and at Sea
The mobility system for Mars-2020

Richard Rieber
Mars2020 Mobility Systems Engineer

23 May 2018

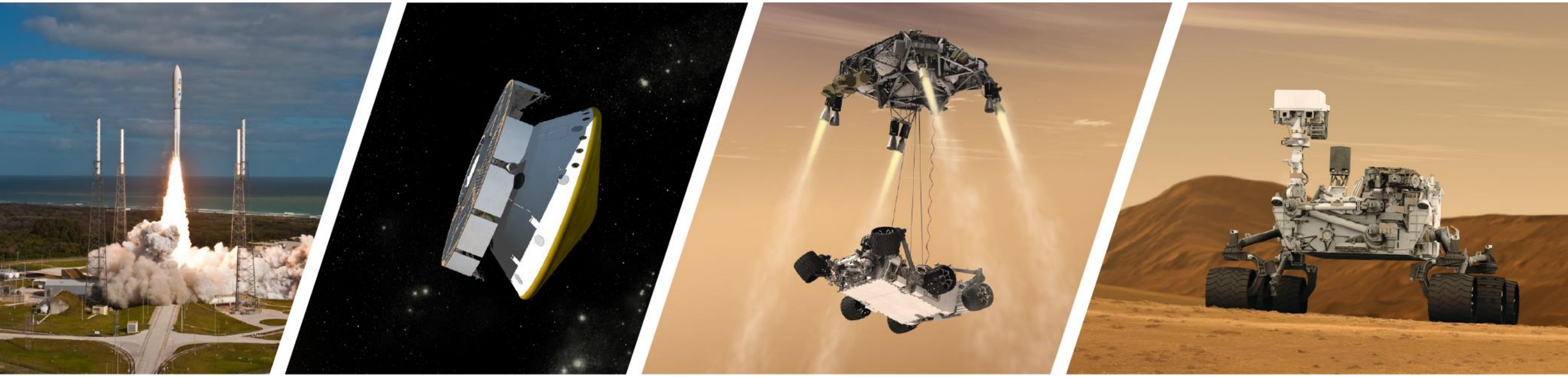


Mars 2020 Project

Overview

- M2020 overview
- Martian Challenges
- Autonomy in rover planning
- Autonomous Navigation
- Automated Rover Localization
- Maritime applications
- Advice to others

MISSION TIMELINE



LAUNCH

- Atlas V 541 Class Rocket
- Period: Jul/Aug 2020

CRUISE/APPROACH

- 7.5 month cruise
- Arrive Feb 2021

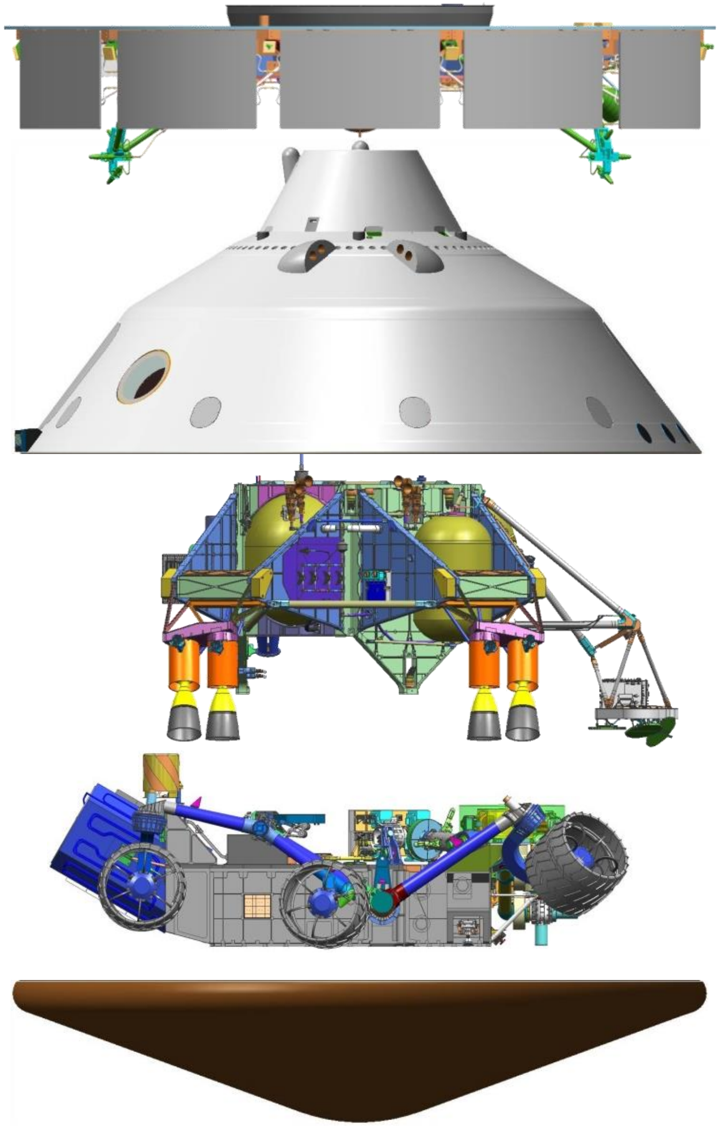
ENTRY, DESCENT & LANDING

- MSL EDL system: guided entry and powered descent/Sky Crane
- 25x20km landing ellipse
- Access to landing sites ±30° latitude, ≤0.5 km elevation
- ~1050 kg rover

SURFACE MISSION

- Prime mission of 1.25 Mars-years
- 20 km traverse distance capability
- Seeking signs of past life
- Returnable cache of samples
- Prepare for human exploration of Mars

MSL Heritage Flight System Concept



Cruise Stage Vehicle: Build to print

Backshell/Parachute: Build to print

Descent Stage Vehicle: Build to print

Rover: High heritage; Replacing Engineering cameras; New instrument suite; New Sampling and Caching system; New Vision Compute Element

Heatshield: Build to print

M2020 Rover Key Features

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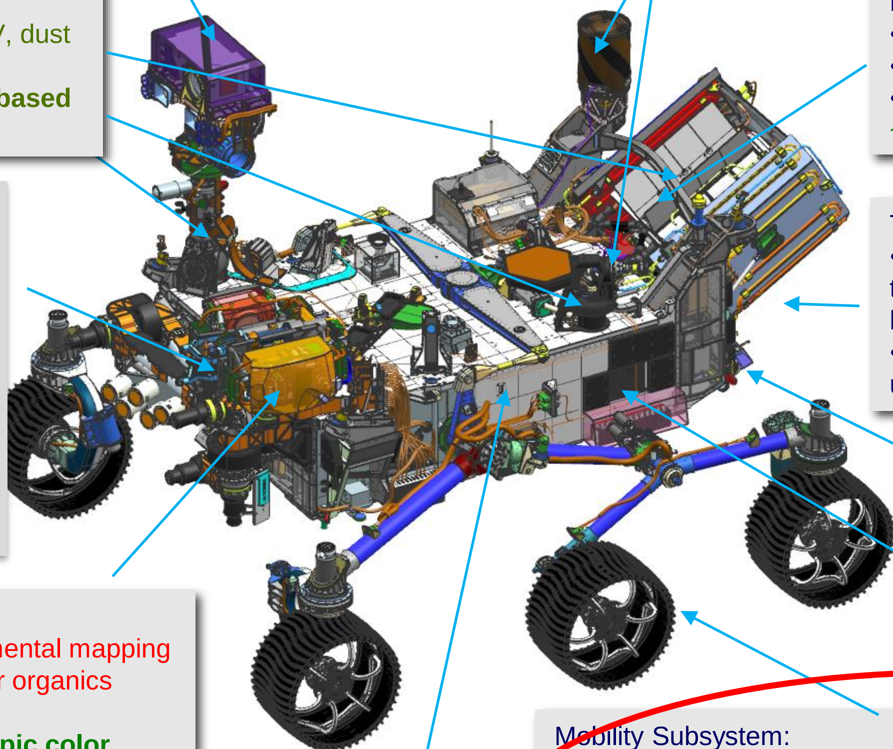
Pan/Tilt Remote Sensing Mast (RSM):
- MASTCAM-Z - stereo color science cameras plus zoom feature
- SuperCAM - remote chemical analysis via LIBS, IR and green Raman
  - **Directional microphone**
- **NAVCAMs - stereo engineering cameras (select targets, plan driving)**

Telecom Subsystem:
- UHF to MRO/MAVEN, daily overflights provide >250 Mbits/sol
  - **Advanced LDPC coding for improved link throughput**
- Xband - SDST + 15W SSPA + pointable HGA + omni LGA

Environmental Science:
- MEDA - temperature, pressure, UV, dust and wind sensors
- **Retroreflector for future orbiter-based laser atmospheric experiments**

Power Subsystem:
- 28V shunt regulated power bus
- Continuous RTG power ~100W
- Re-chargeable Li-Ion Batteries ~3000Whr nameplate capacity



Sample Cache Subsystem:
- 5 DOF 2m long robotic arm
- Abrader/**Gas Dust Removal** tools Rotary percussive drill to acquire solid rock core
- Internal sample prep including tube sealing and imaging capabilities
  - **CC/PP Witness tubes**
- **High-level behaviors such as Go and Hover**

Thermal Control Subsystem:
- Pumped Freon fluid loop provides temperature control for internal hardware
- Survival heaters and warm-up heaters used for external hardware

RIMFAX – Ground penetrating radar used during traverse

Avionics Subsystem:
- Redundant computers
- Autonomous activity execution
- **Enhanced compression**

In-Situ Science:
- PIXL – X-ray spectrographic elemental mapping
- SHERLOC – Deep UV Raman for organics detection
- **WATSON - focusable microscopic color imager (MSL MAHLI heritage)**

Mobility Subsystem:
- Rocker-bogie suspension with 6 wheel drive, 4 wheel steering
- Terrain-robust wheels
- **Enhanced load capability for 1050kg rover**
- Front and **rear stereo HAZCAMs**
- 100m/hr blind drive, 75m/hr **Enhanced Autonav**

Human Exploration Technology: MOXIE oxygen generation plant

Key:
New for M2020
Updated for M2020
Heritage

BOLD Update from PDR

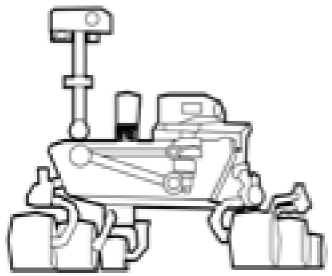
Challenges

- Comm:
  - One-Way Light Time varies 4-min to 24-min
  - Downlink: 150-MB/Sol
  - Limited communication opportunities
- Power:
  - 110-watts of power
- Computer:
  - 133MHz RAD750 (~Pentium-1 processor)
- Temperature
  - Winter: -100C to -40C
  - Summer: -80C to +0C
  - Actuators must be above -55C to function

MSL vs. Mars2020 Mission Comparison

1.25 MARS YEARS
context

MSL



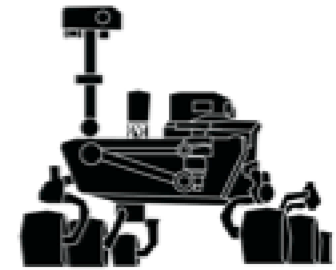
MARS YEARS:
1.25

DISTANCE COVERED:
10.6 km

SAMPLES COLLECTED:
2 scooped
6 drilled samples

M2020 Surface Mission MUST perform significantly better relative to MSL in order to accomplish mission objectives.

M2020



MARS YEARS:
1.25

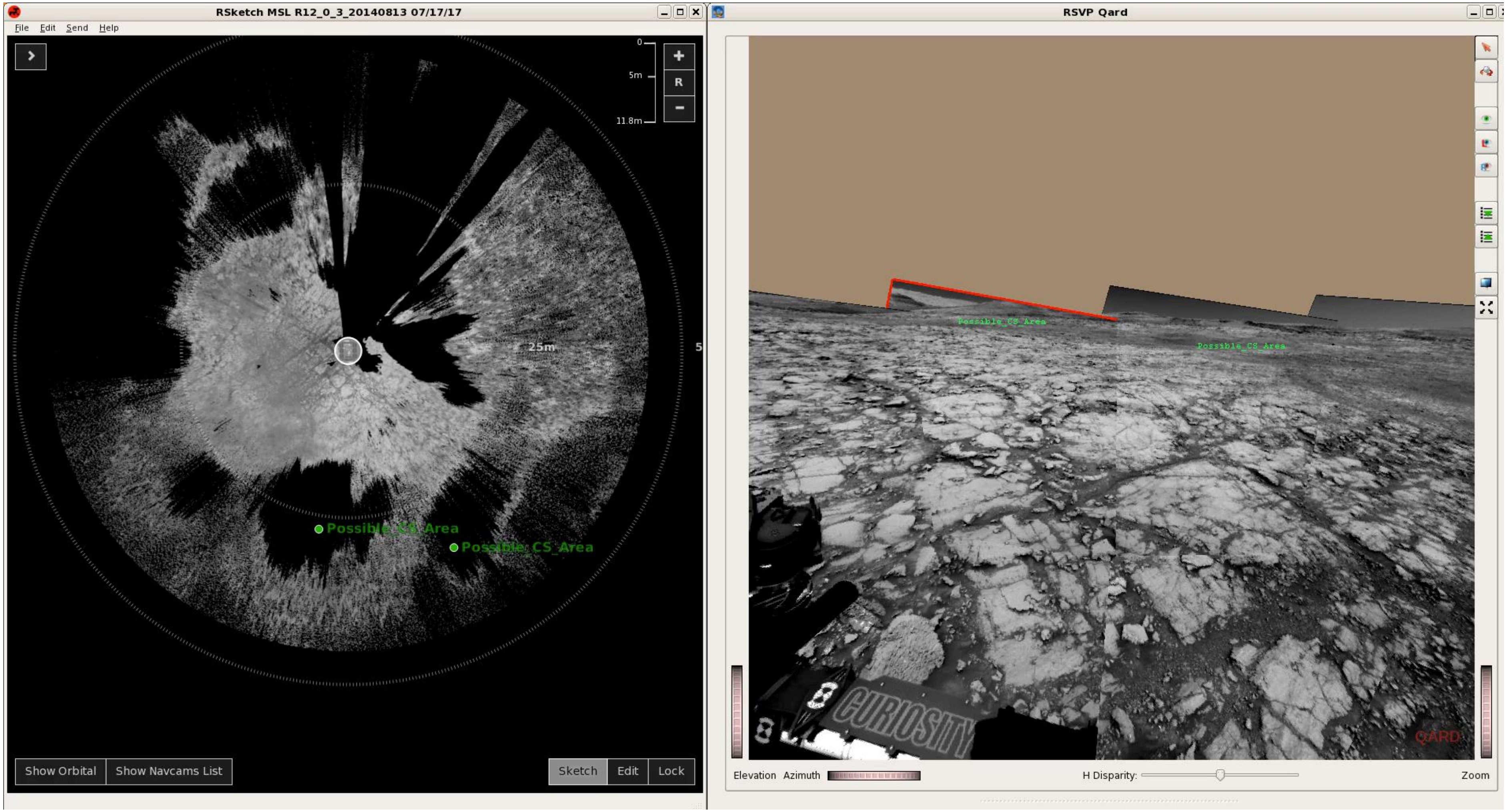
DISTANCE TO COVER:
15 km

SAMPLES TO COLLECT:
20 drilled samples

Drive Planning

RSketch

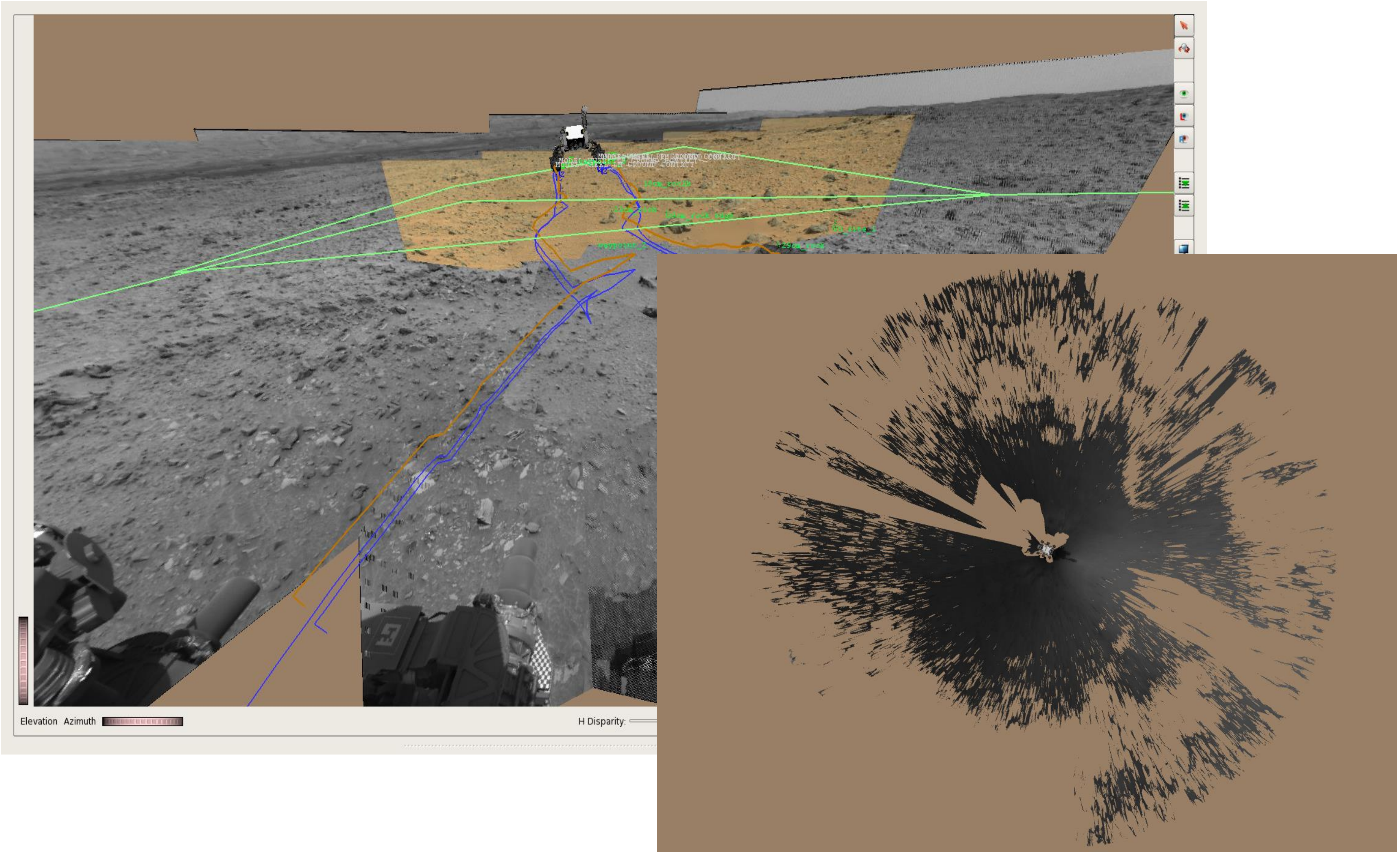
Rsketch lead developer: Nick Wiltsie



AutoNav

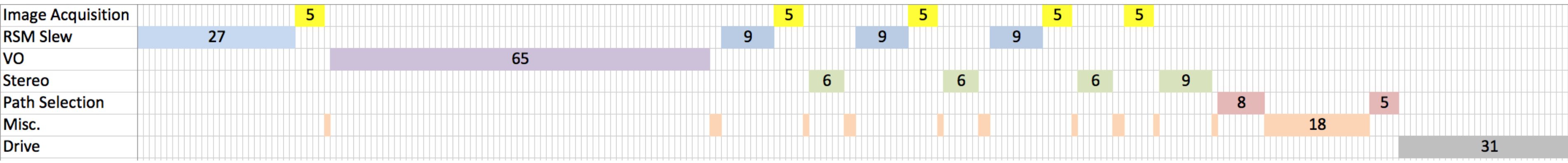
Faster and Assertive

Why AutoNav?



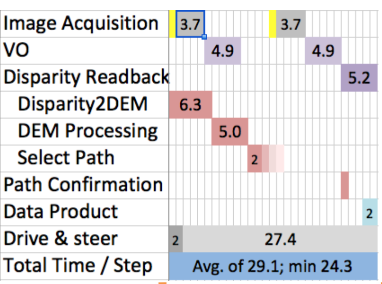
Thinking while Driving

MSL



247 sec/meter
~15 m/hr

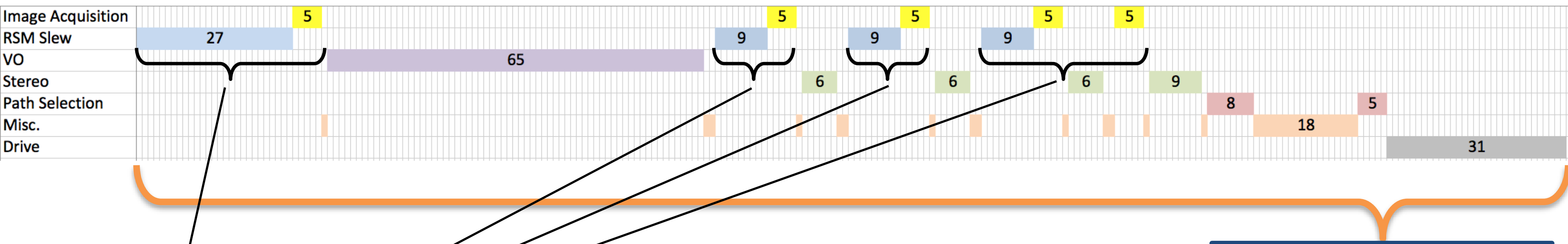
M2020



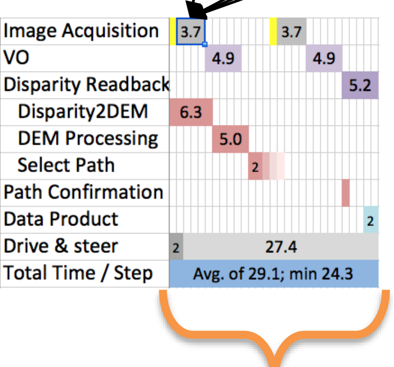
30 sec/meter
~100 m/hr

Thinking while Driving

MSL



247 sec/meter
~15 m/hr



M2020

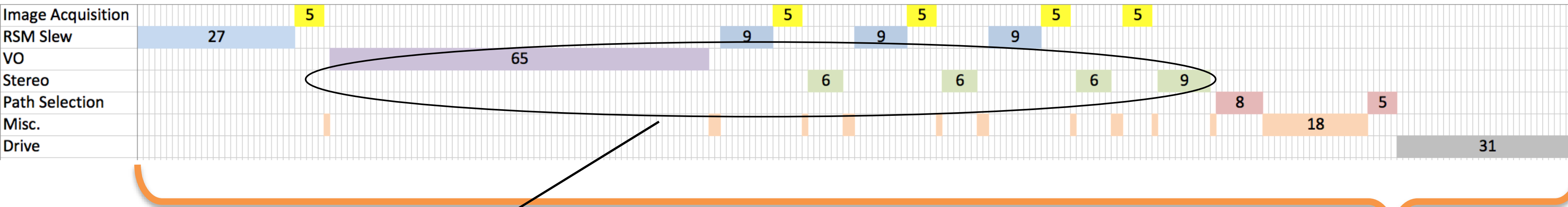
30 sec/meter
~100 m/hr

Camera upgrade:

- Wider field of view allows a single exposure to capture area ahead of rover
  - No camera mast movement
- Shorter exposure duration allows imaging while driving
- Faster image readout.

Thinking while Driving

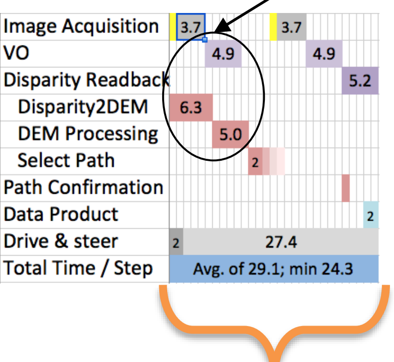
MSL



247 sec/meter
_~15 m/hr_

Additional computer:

- Vision Compute Element (VCE)
- 3rd RAD750 and Vertex5 FPGA
- Dedicated to image processing
- Used for Visual Odometry and Stereo processing

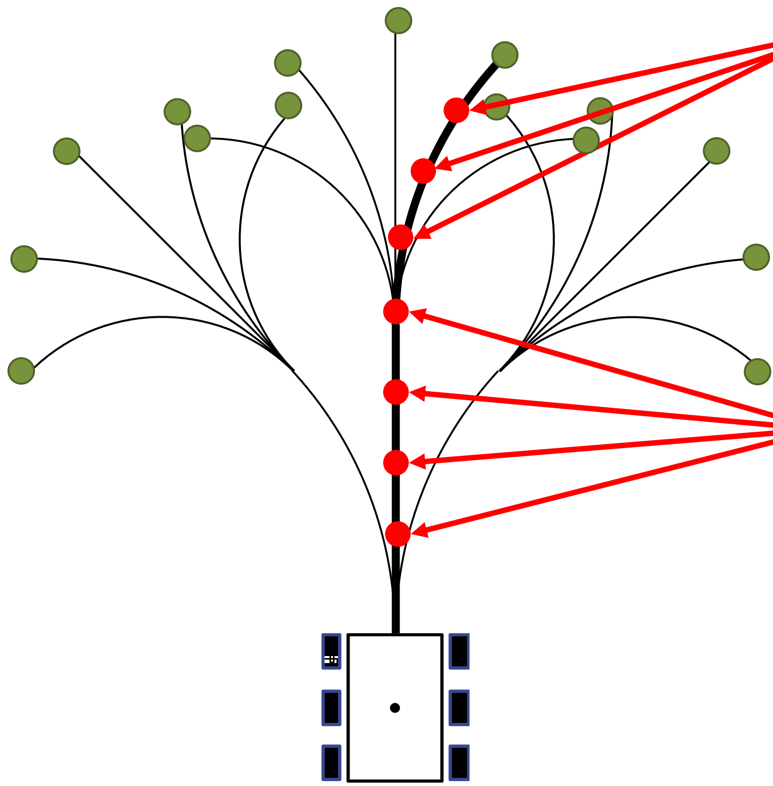


M2020

30 sec/meter
_~100 m/hr_

AutoNav – more assertive

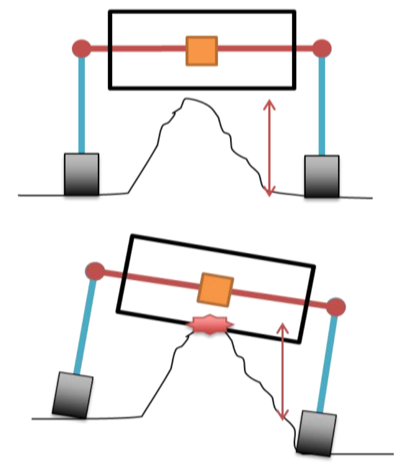
Local Planner



- Selects best path for the next 6m from finite # of options

ACE

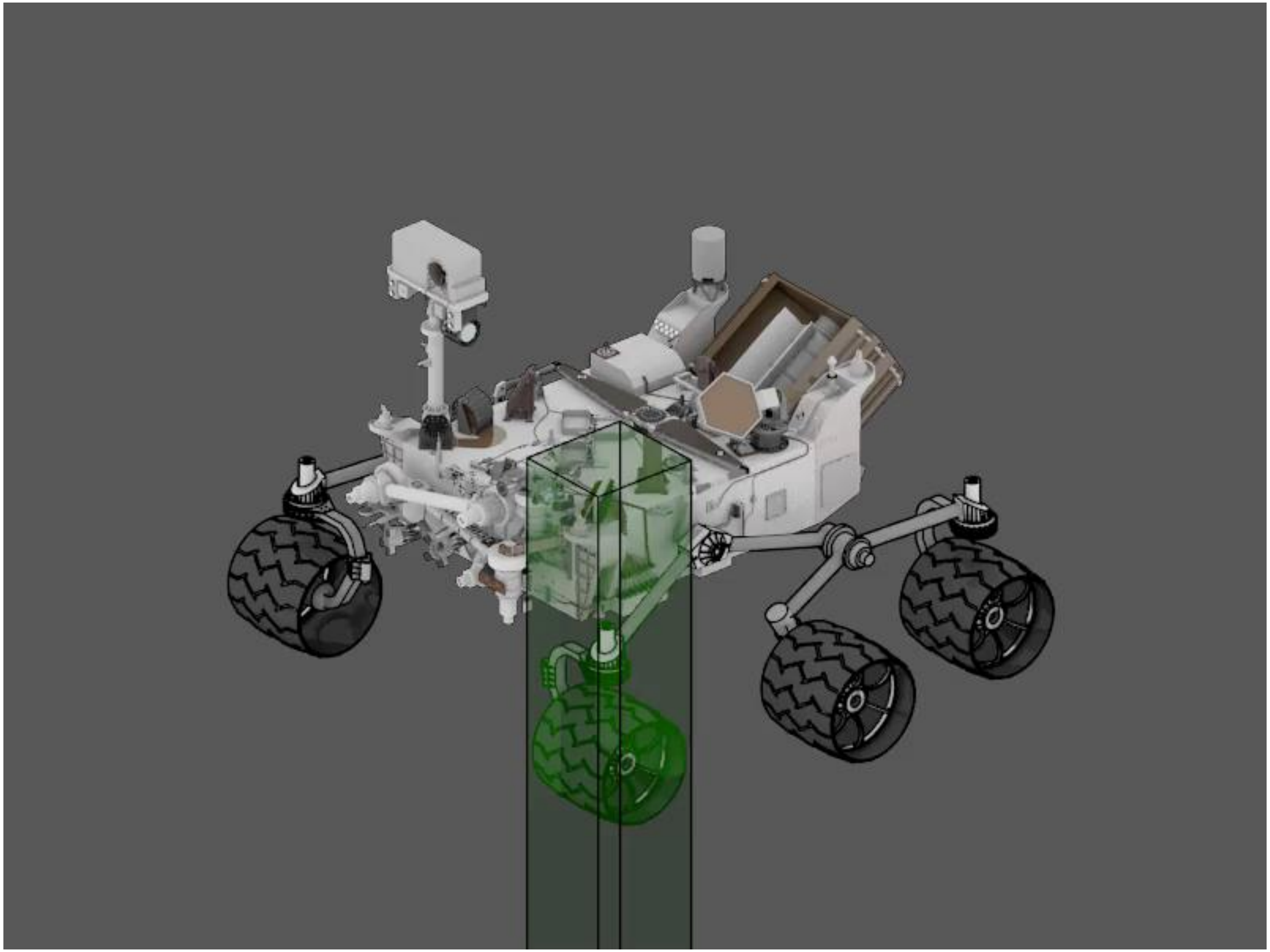
(Approx. Clearance Est.)



- Checks clearance, wheel drop, pitch, roll, tilt, suspension angles, & unknown terrain every 25cm or 10° for TIP

ENav team: Oliver Toupet, Hiro Ono, Tyler del Sesto

ACE



AutoNav in action!

ENav Mars Yard test on Scarecrow
February 7, 2018

NAVLIB/Enav
Olivier Toupet, Tyler Del Sesto, Hiro Ono, Mike McHenry

Caspian Visualization
Nat Guy

RSFW & SSDev
Jeff Biesadecki, Steven Myint, Todd Litwin, Mark Maimone

Scarecrow RSM
Jackie Sly

ROLO (ROver LOcalization)

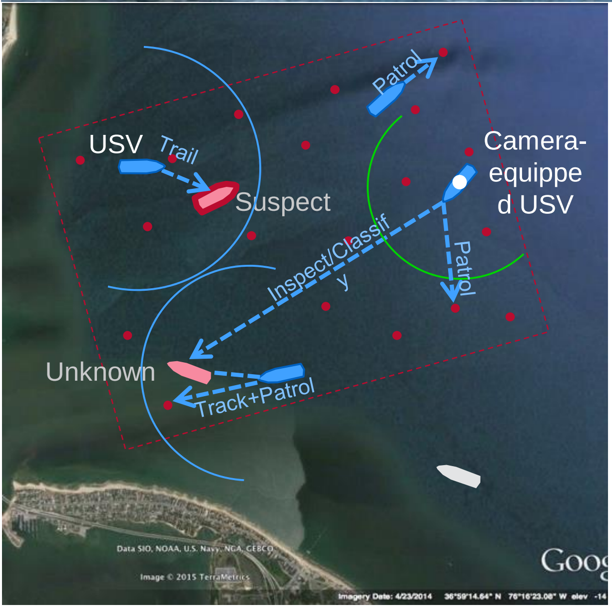
Overview: IDS tool used to manually verify auto-localization results through visual inspection and/or create new localizations using the sliding method or tiepoints.

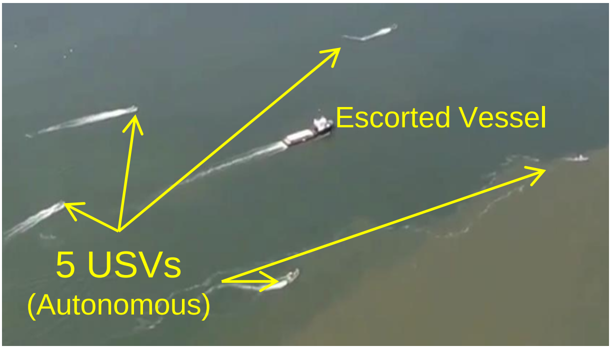
Localization methods:

- Sliding
  User moves ortho images over basemap to compare ortho features against basemap features
- Tiepointing
  User selects corresponding points between ortho images and basemap. Average difference between tiepoints in solution used to generate new localization

Features:

- CWS integration
- Localization results pushed to PLACES database
- Displays traverse path and waypoint data
- Provides metric comparison between telemetered, auto-localization, and manual-localization solutions





Mission-level autonomy for long duration operation under sparse supervisory control, with onboard self-contained sensing and decision making.

Distributed, autonomous mission planning and replanning

CARACaS (Control Architecture for Robotic Agent Command and Sensing) is a JPL autonomy architecture and software suite.

Multi-agent. Multi-mission. Dozens of full-scale platforms, tens of thousands in-water autonomous vehicle-hours.

Autonomous Guidance, Navigation, and Control for safe control of high speed vehicle groups in cluttered environments.

Sponsors include ONR, DARPA, OSD, NOAA.

Maritime and Multi-Agent Robotics, 347N

https://www-robotics.jpl.nasa.gov/groups/MaritimeandMultiAgent/

Michael Wolf (Group Supervisor)
wolf@jpl.nasa.gov

 This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Office of Naval Research through an agreement with the National Aeronautics and Space Administration.

Advice to others

- Research previous experience and heritage to understand inefficiencies in the entire product life cycle
- Autonomy can be difficult and expensive
  - Apply Autonomy where it can have the largest return on investment
- Any autonomy will have a user interface and most likely large quantities of data
  - Architect that interface to be intuitive and present information in a concise fashion

Conclusions

- The Mars2020 mobility system is an immense team effort
  - Over 85 people contribute directly to the mobility effort at JPL
  - Hundreds more at JPL contribute tangentially

- The mobility system is improved by:
  - Intuitive, visual drive sequencing,
  - Aggressive, fast autonomous navigation software, and
  - Redesigned, rugged tires

- All of this enables the Mission's overarching astrobiology and science objectives.

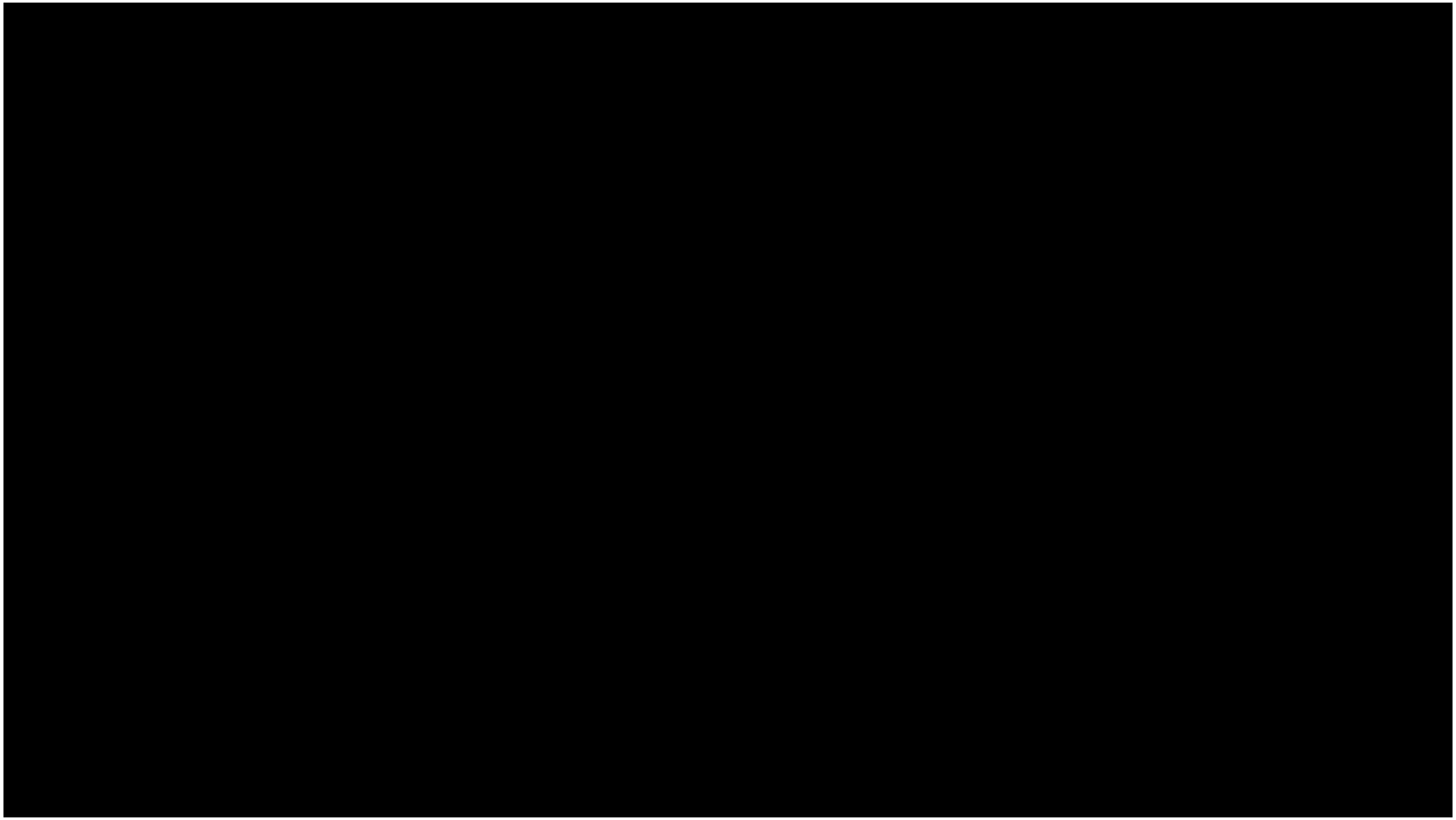
New Tires

MSL's Wheel Wear

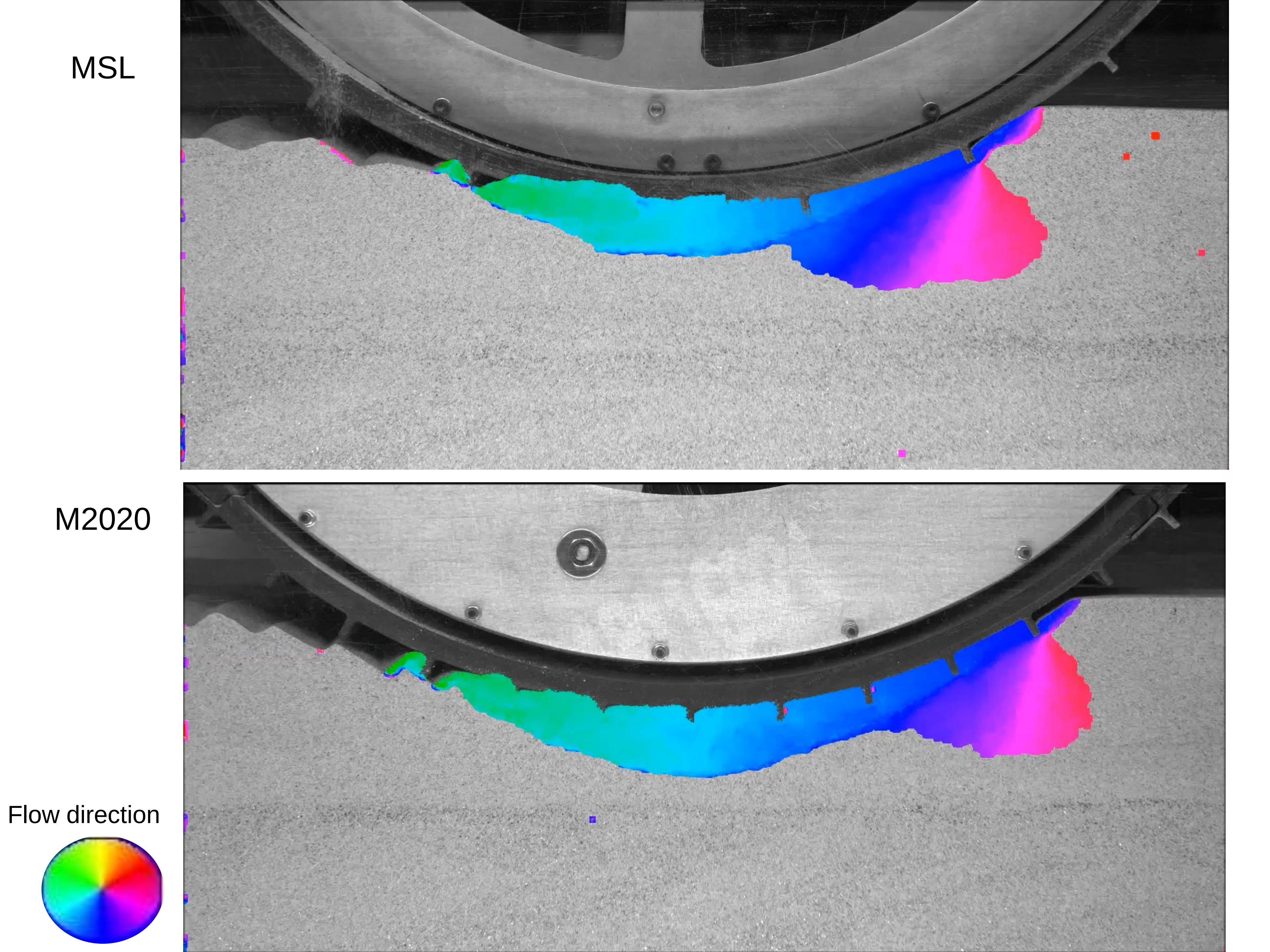
Ventifacts

- Earth rock is primarily eroded by water, leaving smooth edges
- Martian rock is primarily eroded by wind, which leaves incredibly sharp edges
- MSL tire design did not consider inter-mobility forces

MSL's Wheel Wear

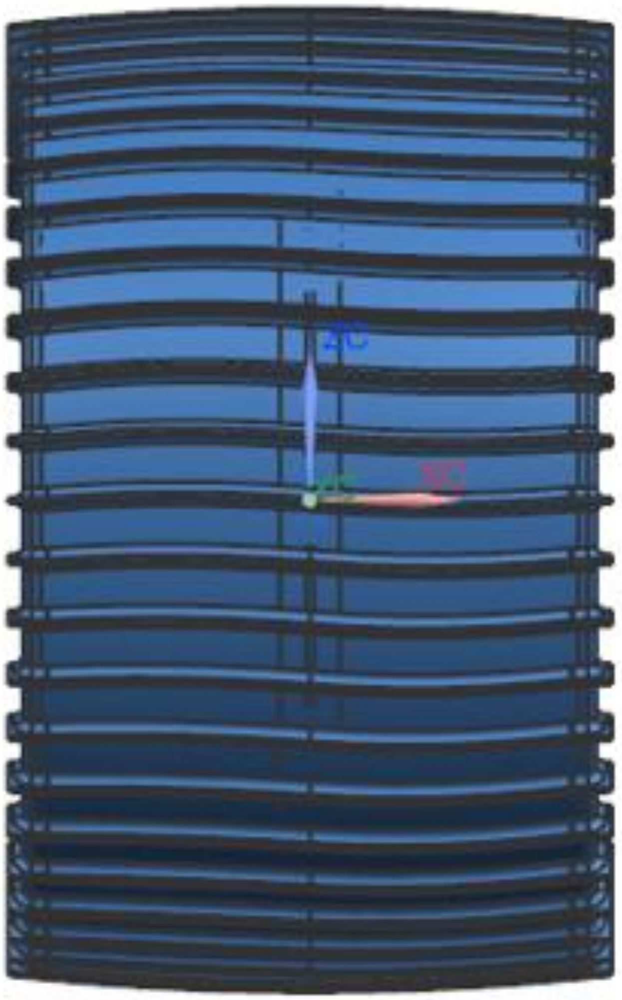


We need a new tire!



MSL
M2020
Flow direction

Final tread design

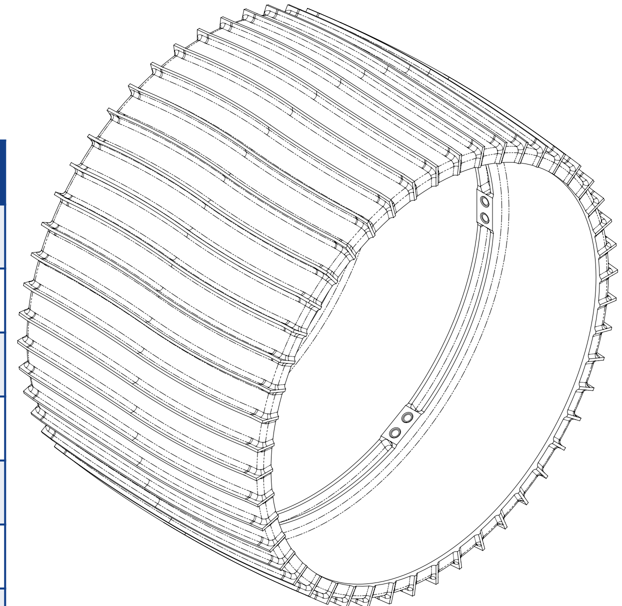


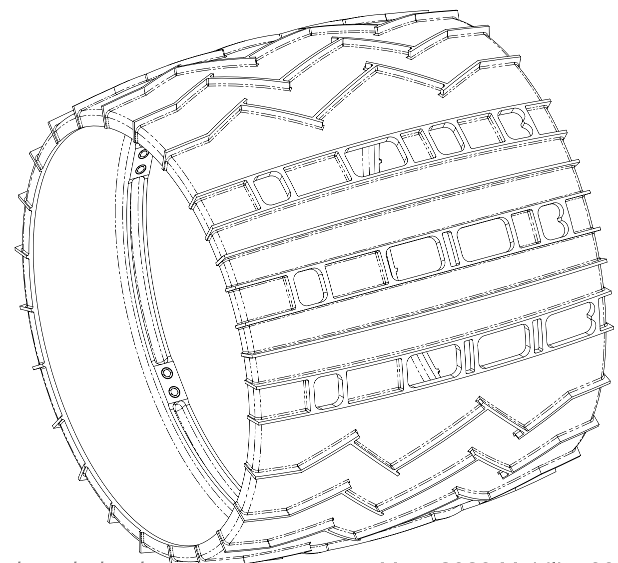
Designing for durability

Tire comparison

Major Differences between Tires

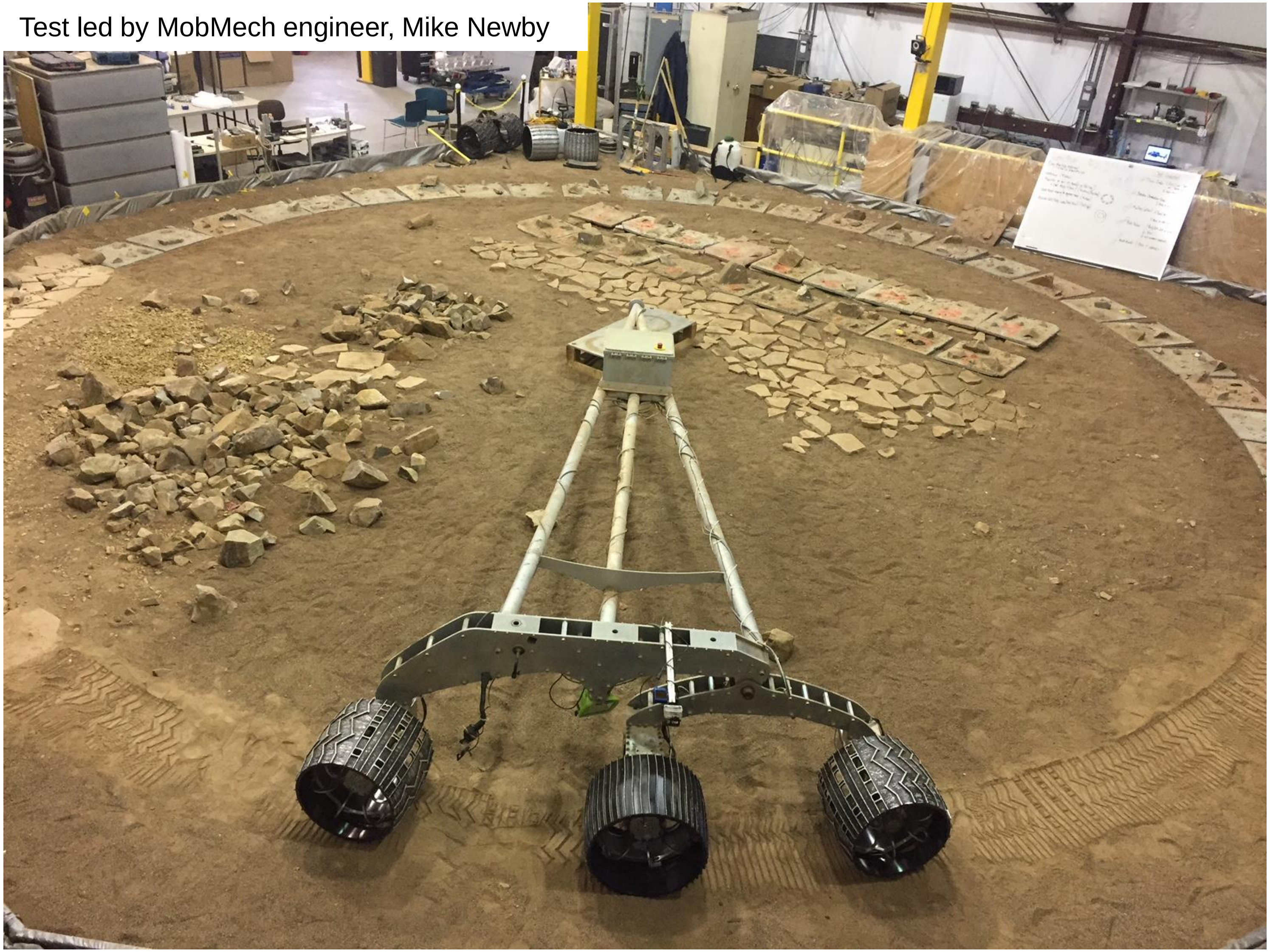
	M2020	MSL
Mass	5.32kg	3.74kg
Skin thickness	1.65mm	0.75mm
Skin centerline diameter	509.25mm	485mm
Width	335.6mm	400mm
Grouser count	48	24
Grouser height	8.25mm	7.5mm
Grouser Shape	Mild sine wave	Aggressive chevron
Flexure interface flange	Centerline	2/3 from edge
Inner diameter coating	Painted	Hard anodized
VO pattern	None	Morse-code





Durability testing

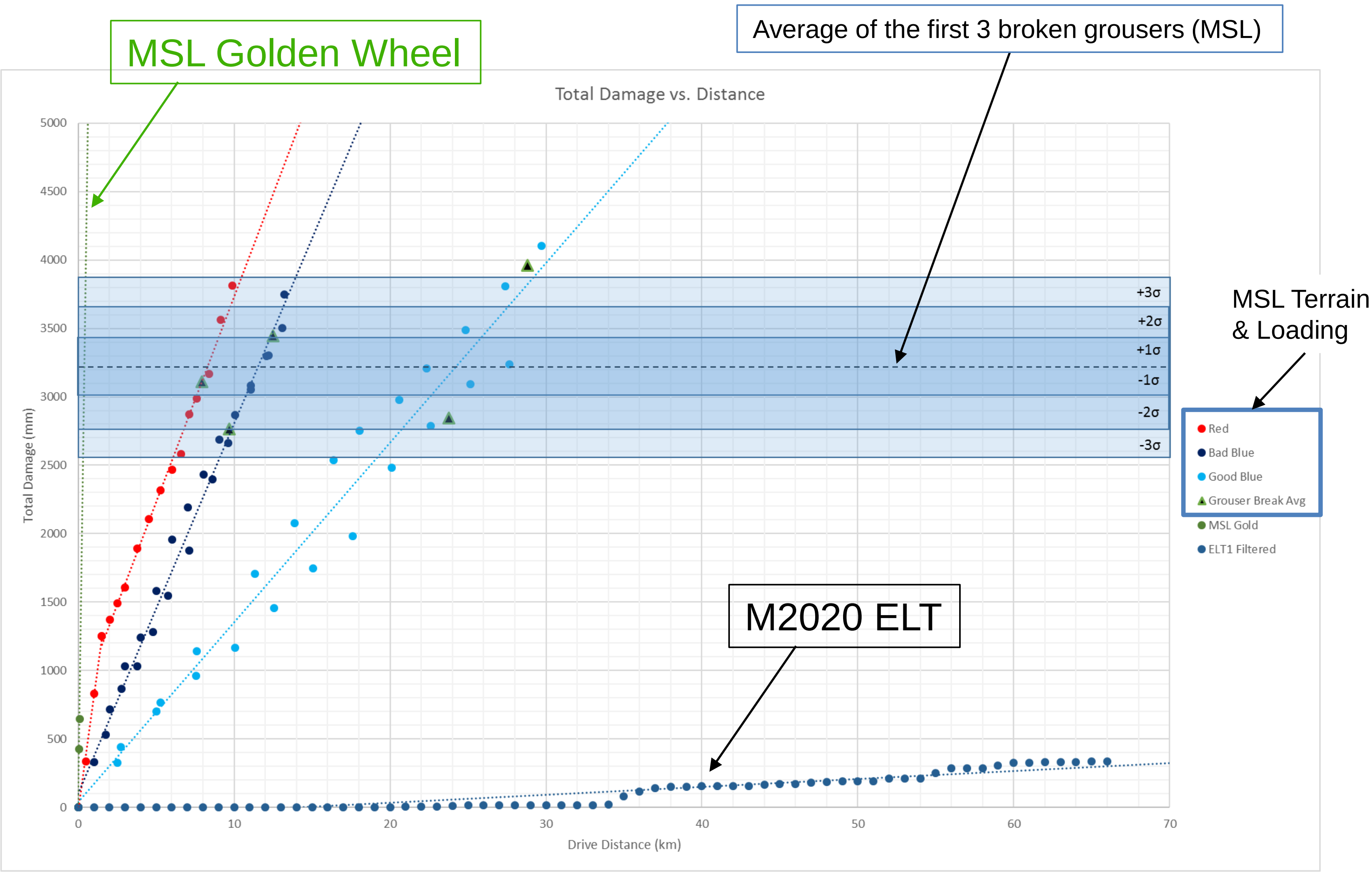
Test led by MobMech engineer, Mike Newby



Durability Testing

Test led by MobMech engineer, Mike Newby

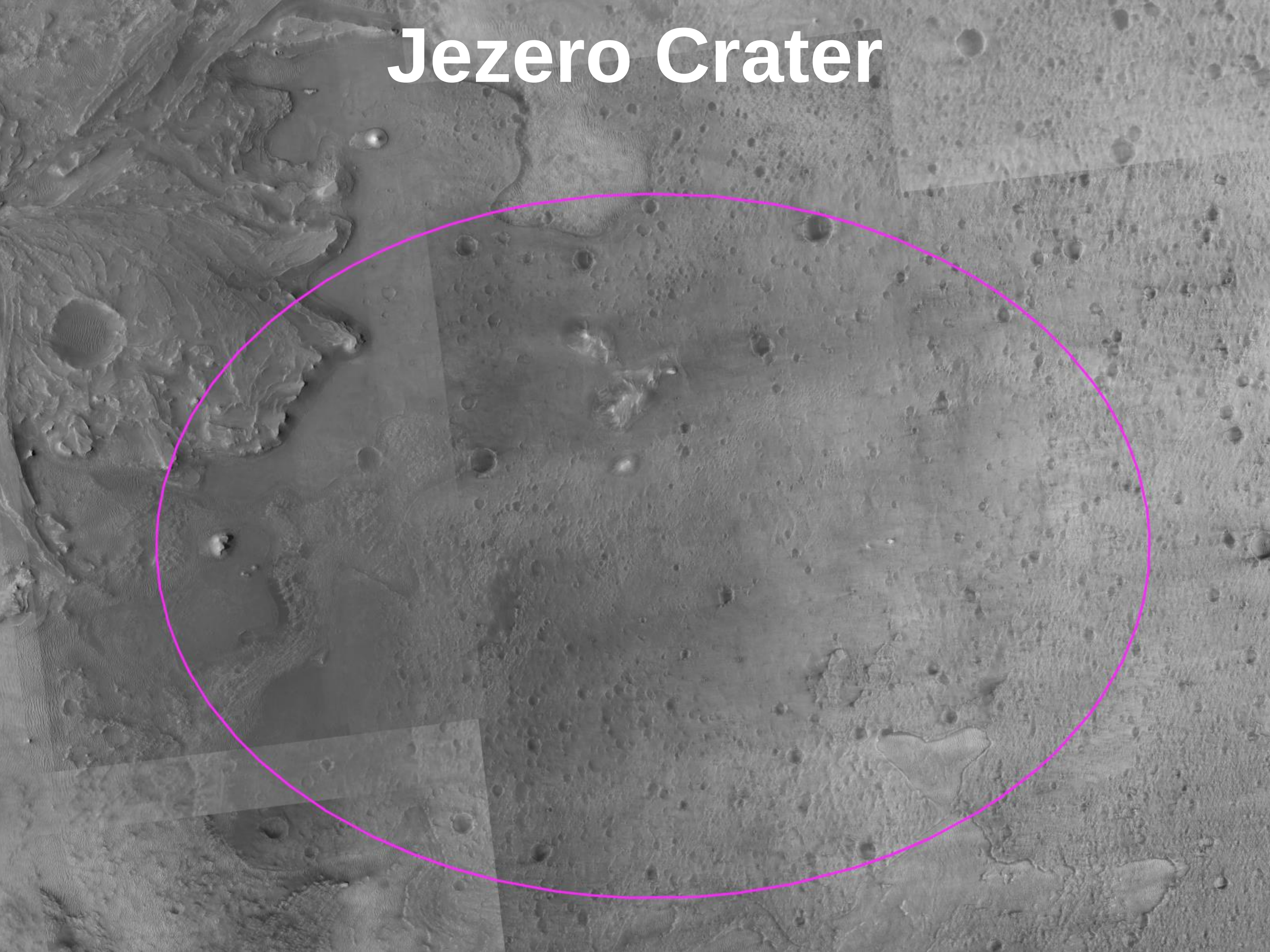
Damage curves



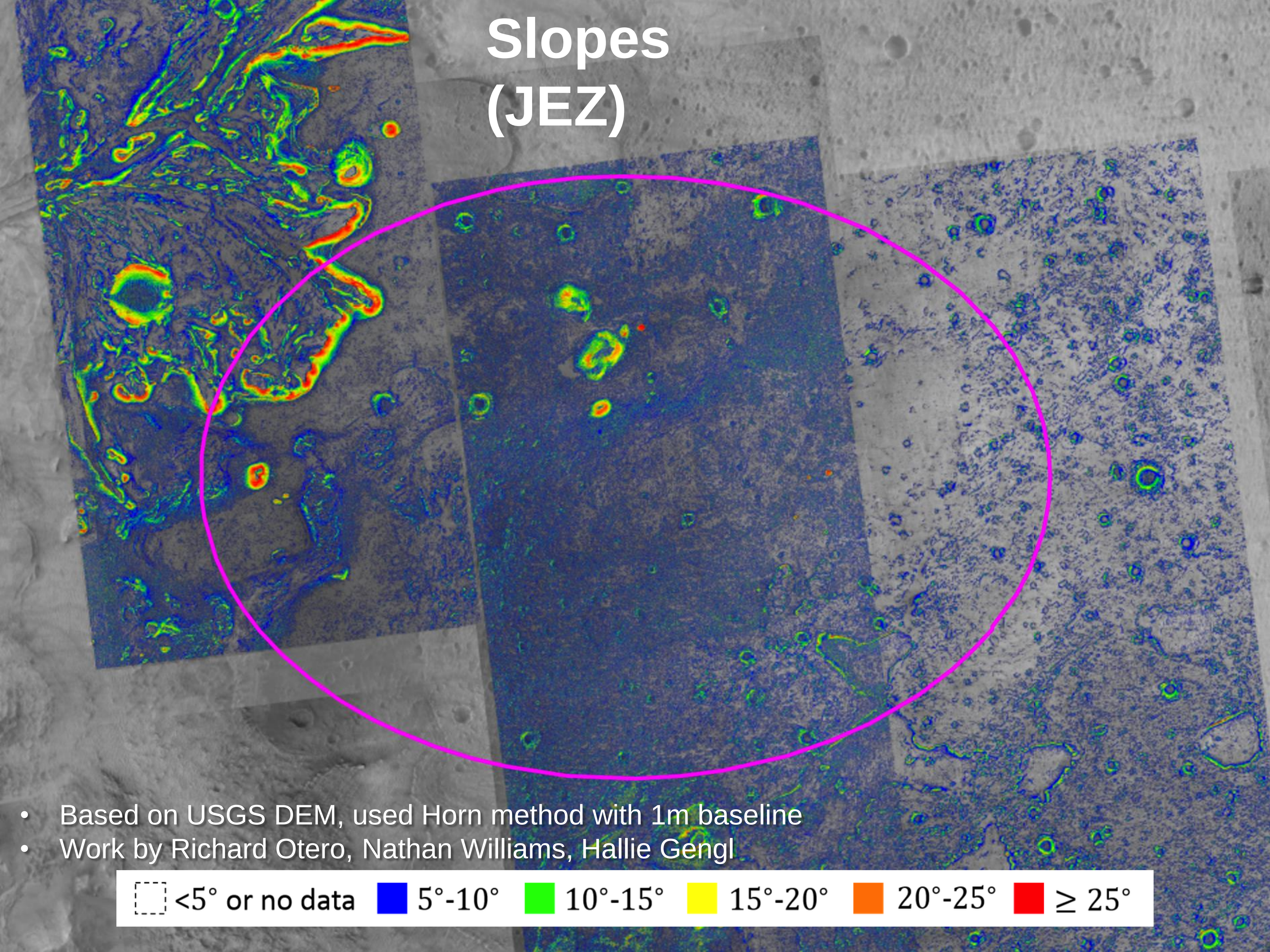
Landing Site Selection

Landing site selection status

Jezero Crater



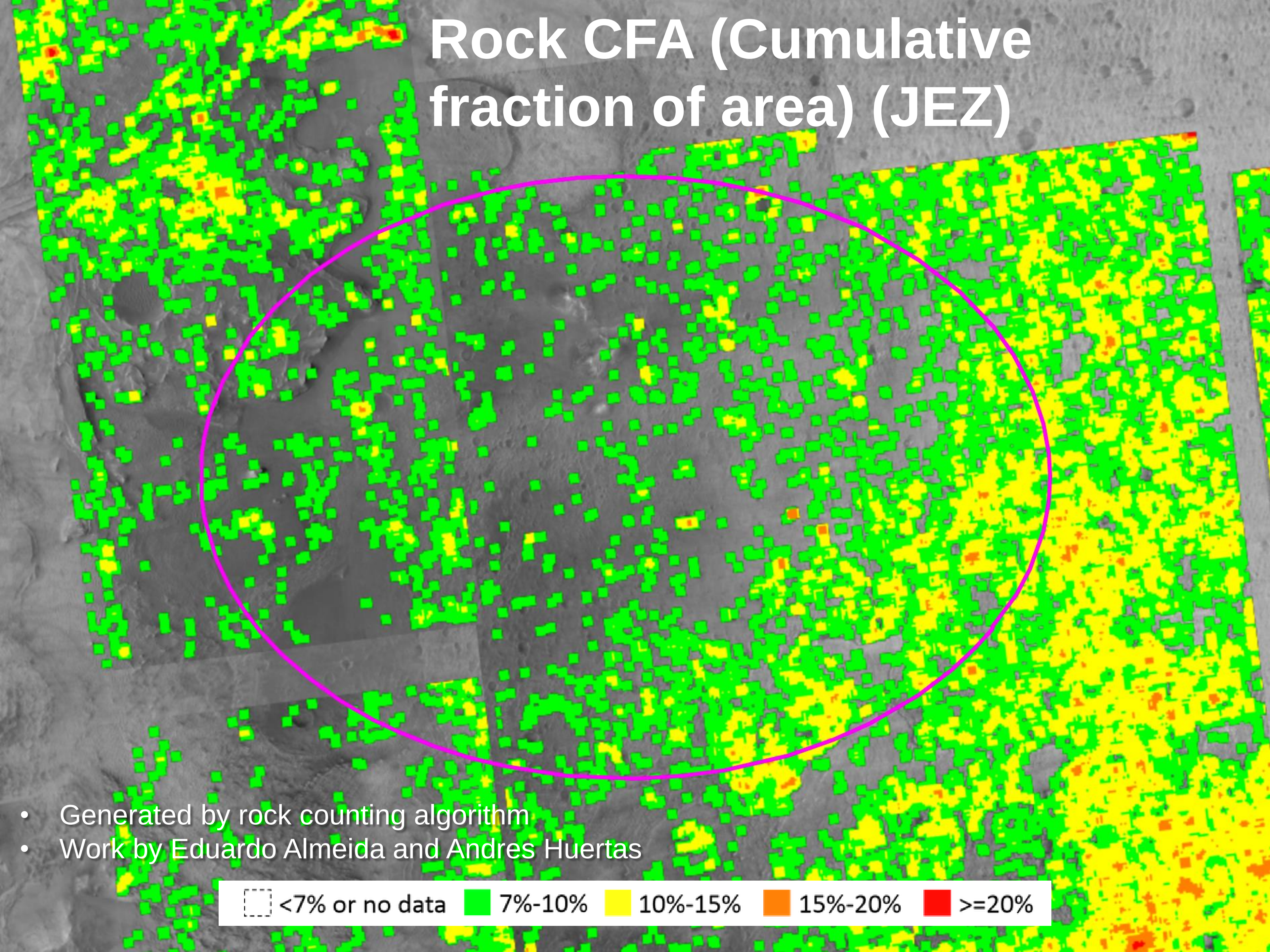
Slopes (JEZ)



- Based on USGS DEM, used Horn method with 1m baseline
- Work by Richard Otero, Nathan Williams, Hallie Gengl

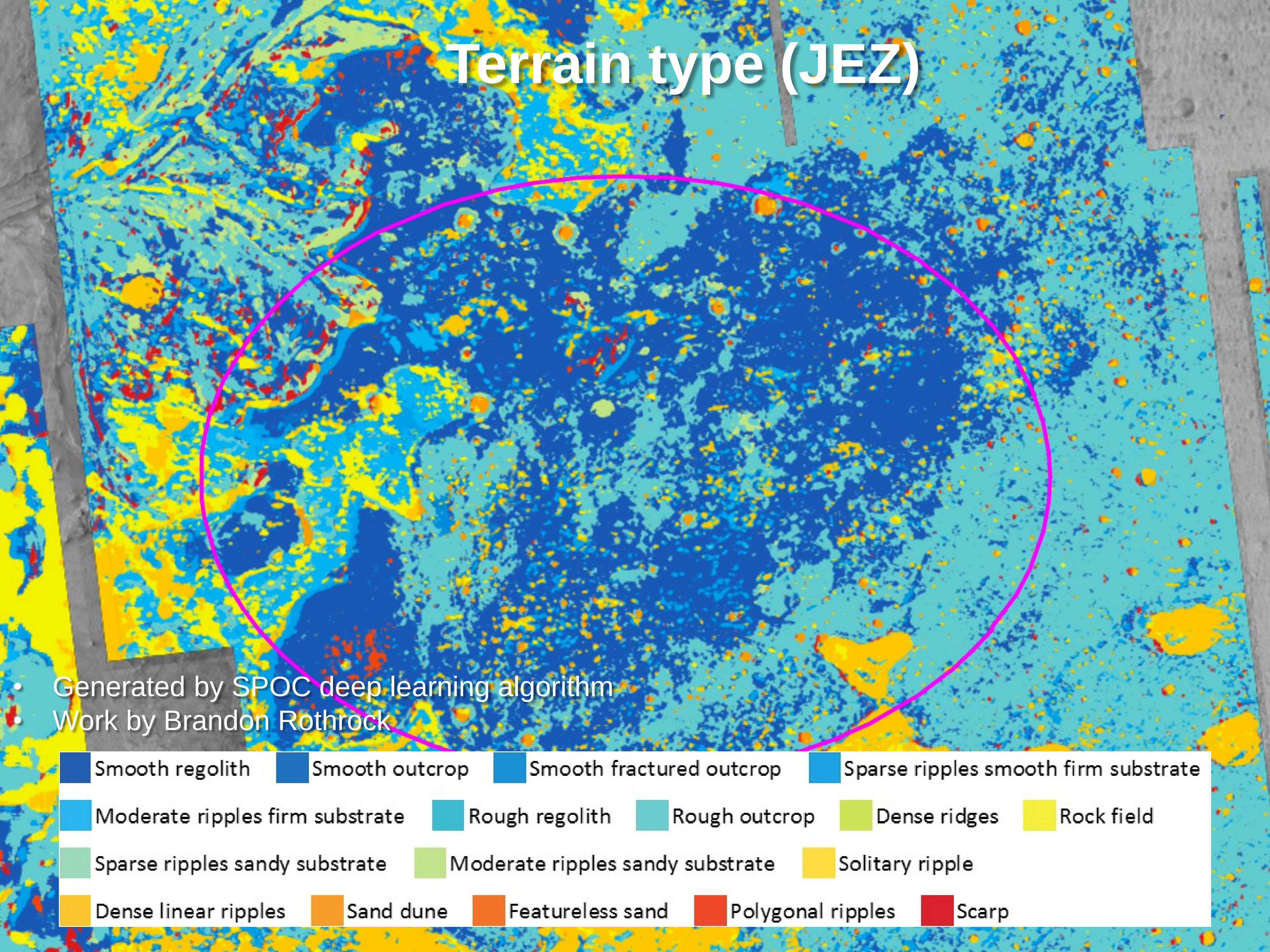
<5° or no data	5°-10°	10°-15°	15°-20°	20°-25°	≥ 25°

Rock CFA (Cumulative fraction of area) (JEZ)



- Generated by rock counting algorithm
- Work by Eduardo Almeida and Andres Huertas

Terrain type (JEZ)

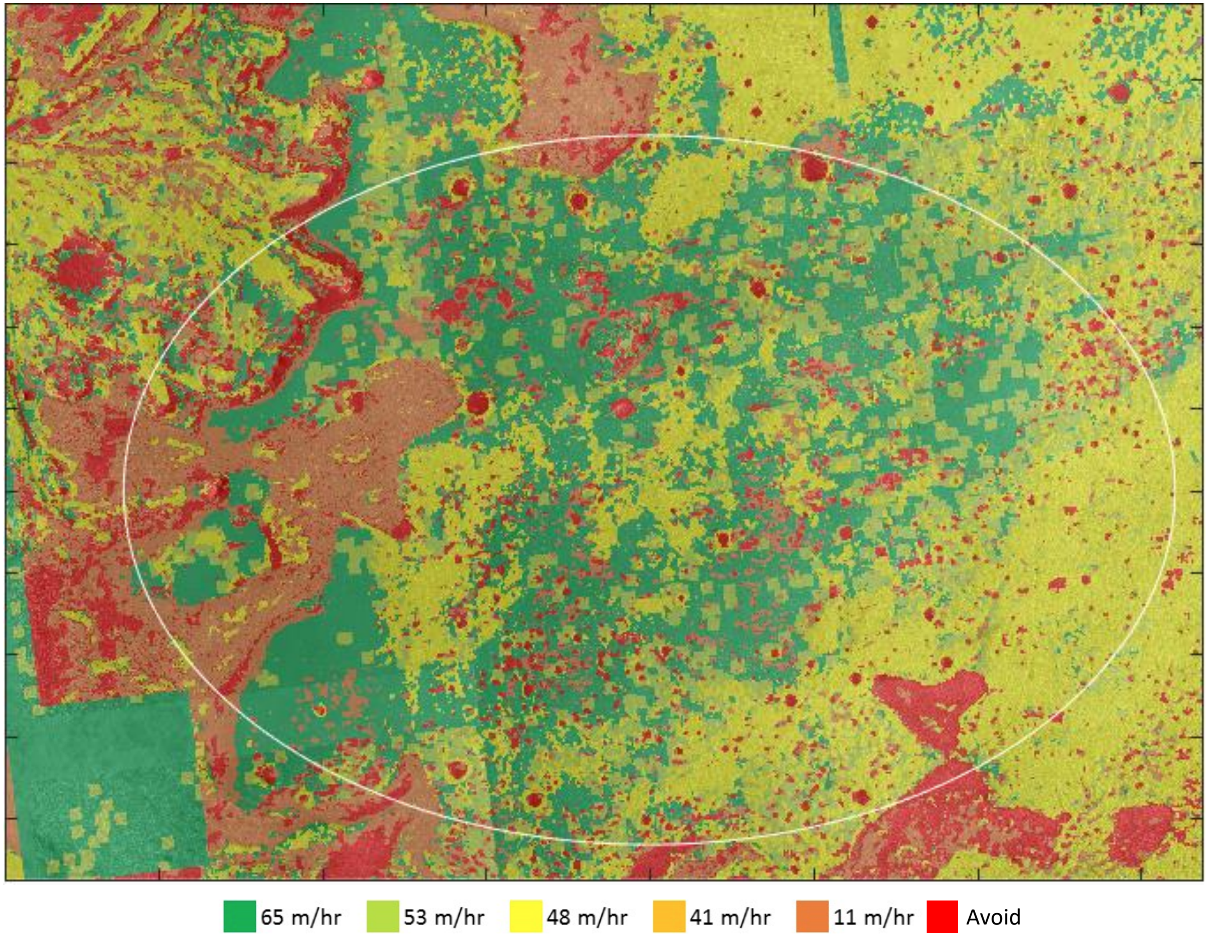


- Generated by SPOC deep learning algorithm
- Work by Brandon Rothrock

Traversability Maps

- Map terrain class/slope/CFA to driving speed at 5 m resolution
- No-data grids are treated optimistically

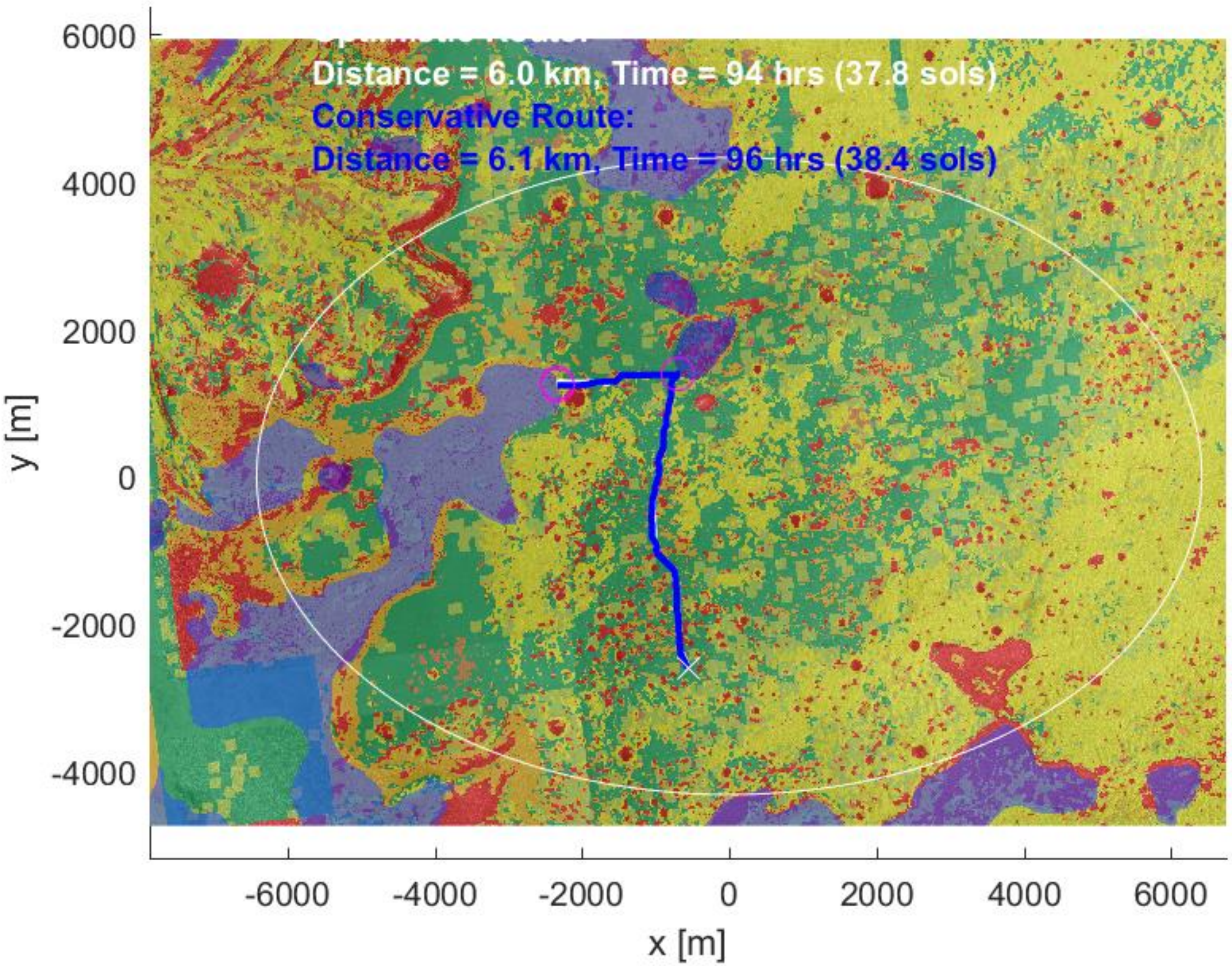
Conservative Traversability Assessment of Jezero



Time-optimal Route Planning

- Plan fastest route from a landing point to two ROIs

Example traverse at Jezero



Monte-Carlo Simulation

- Monte-Carlo simulation with 8,000 landing points sampled from landing probability distribution
- Many routes converge to the most traversable terrains, forming natural “highways”