Jet Propulsion Laboratory
California Institute of Technology

Robotics and Autonomy for Space Applications

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With inputs from: Andrew Johnson, Teddy Tzanetos, Mark Maimone, Michael McHenry, Hiro Ono, Steve Chien, Brett Kennedy

September 8, 2023
UASLP – Universidad Autónoma de San Luis Potosi, Mexico

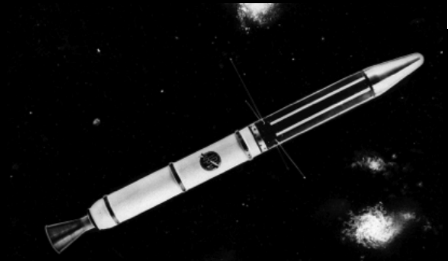
Clearance: CL#23–

NASA’s Jet Propulsion Laboratory

Pasadena, California

- One of 10 NASA centers
- Founded in the 1930s

Many Firsts in Space Exploration

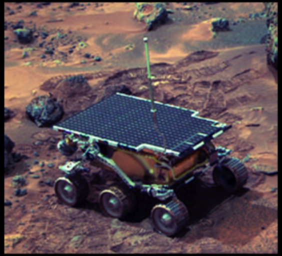


1st U.S. Satellite
1958 – Explorer 1

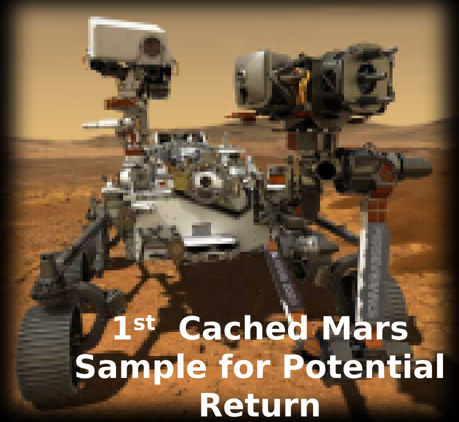
1st Powered Flight on another Planet
2021 – Ingenuity

Voyager 1 & 2

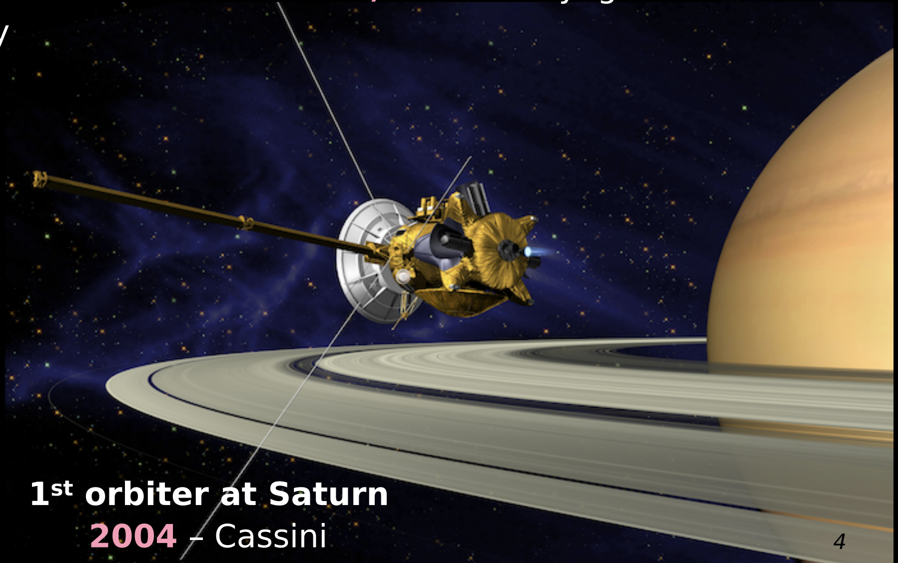
1st Flybys of Neptune/Uranus
1986, 1989 – Voyager 2



1st rover on Mars
1997 – Sojourner



1st Cached Mars Sample for Potential Return
2021 – Perseverance



1st orbiter at Saturn
2004 – Cassini

What Motivates Planetary Exploration?

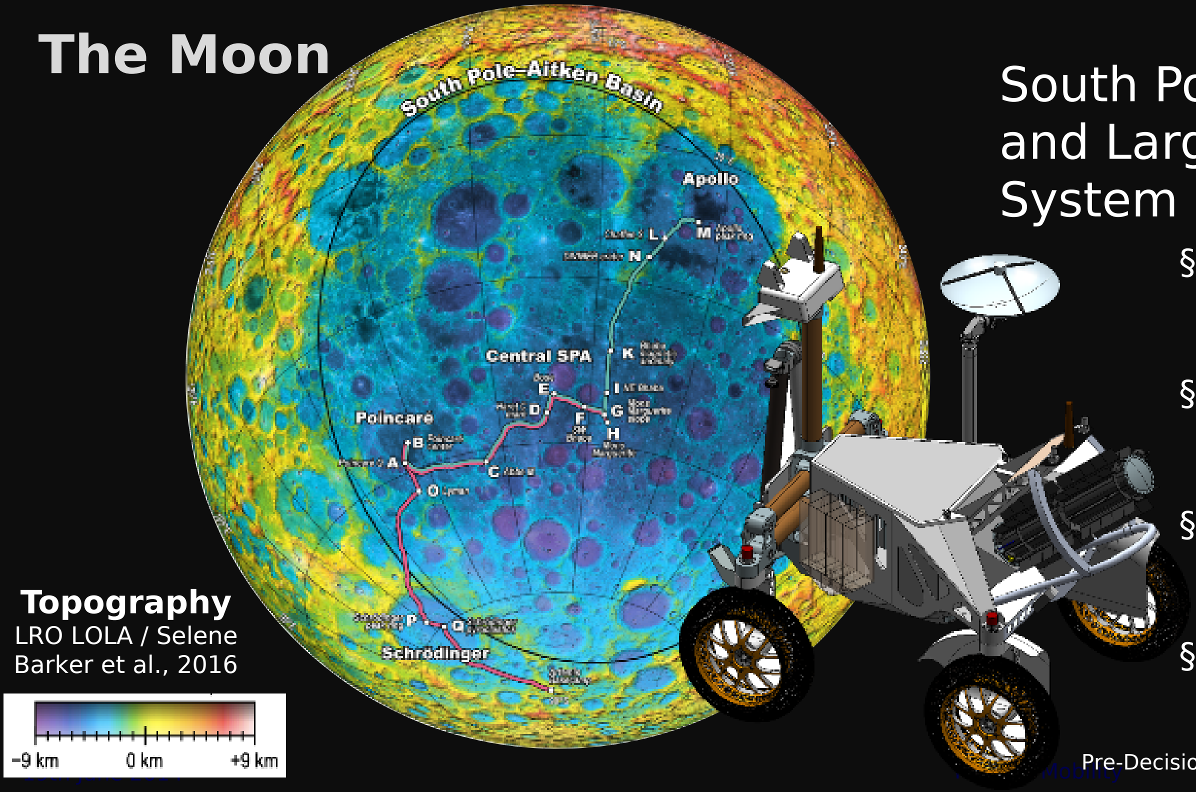
Big science questions:

- **Origins**
- **Worlds and processes**
- **Life and habitability**

Origins

Example: Endurance – Lunar Sample Return Mission Concept

The Moon



Topography
LRO LOLA / Selene
Barker et al., 2016

South Pole Aitken Basin - oldest and Largest Impact Crater in Solar System

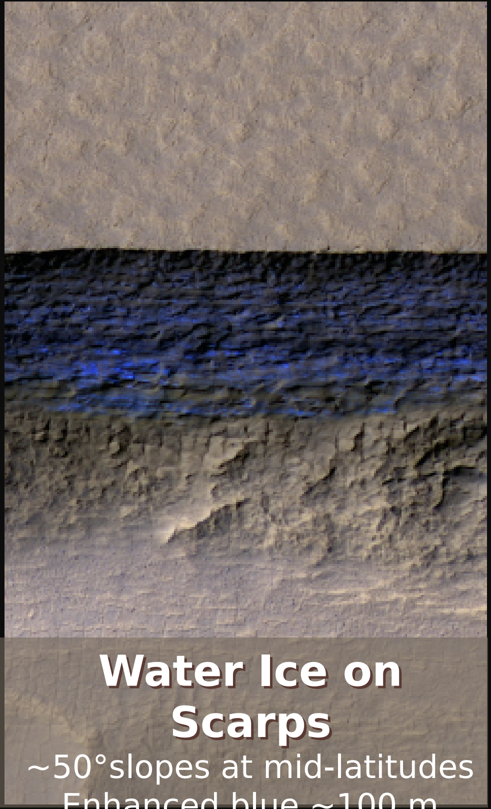
- Collect 12 samples (100 kg) along 2,000 km route
- Drive during day and night
- Bring samples to South Pole
- Astronauts pick up and bring samples to Earth for study

Worlds and Processes

Examples: Uranian System

Evolution of planet, rings, and moons

Martian Ice and Water



Water Ice on Scarps

~50°slopes at mid-latitudes
Enhanced blue ~100 m

Credit: NASA/JPL-Caltech/UA/USGS

Recurring Slope Lineae

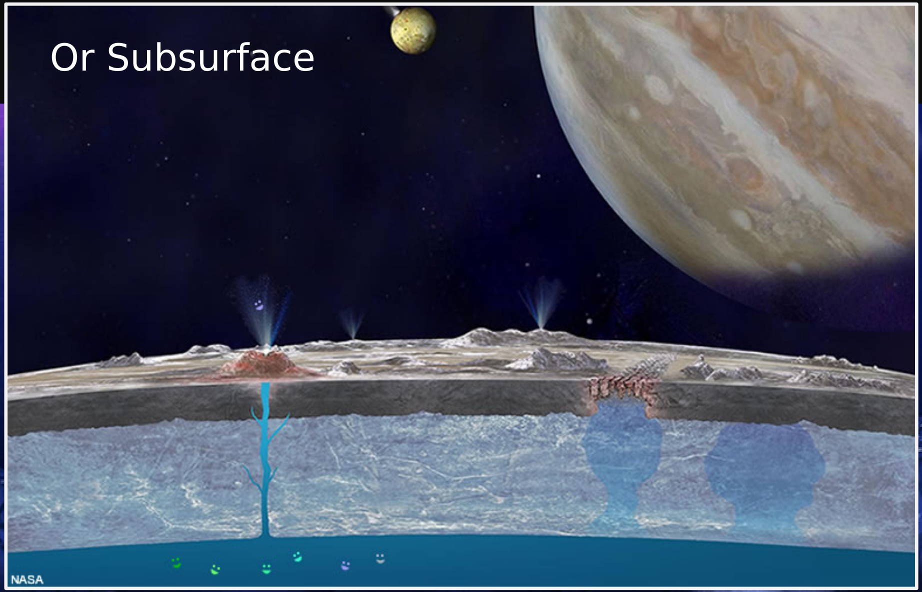
35°slopes

Credit: NASA/JPL-Caltech/UA/USGS
MRO HiRISE

Life and Habitability

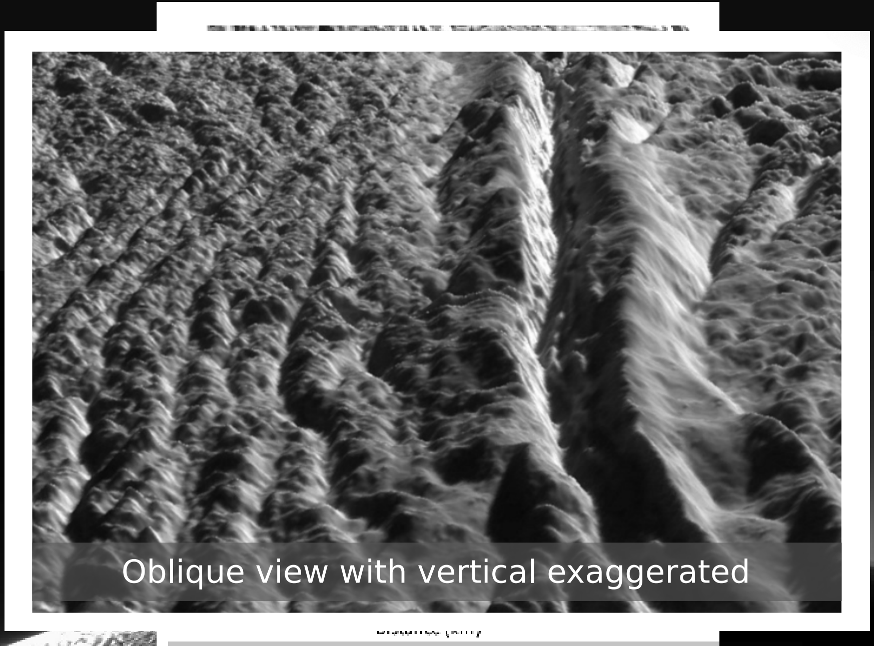
Examples: Ocean Worlds

Europa



Or Subsurface

Enceladus



Oblique view with vertical exaggerated

Plumes of Water Ice

Credit: NASA/JPL-Caltech/Space Science Institute

Robotic Explorers

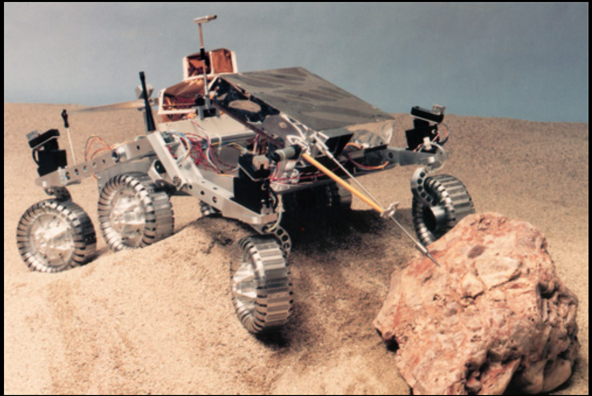
Many Forms

A Long History of Robotics Development


SLRV (1964) (JPL and GM)

Blue Rover (1986)

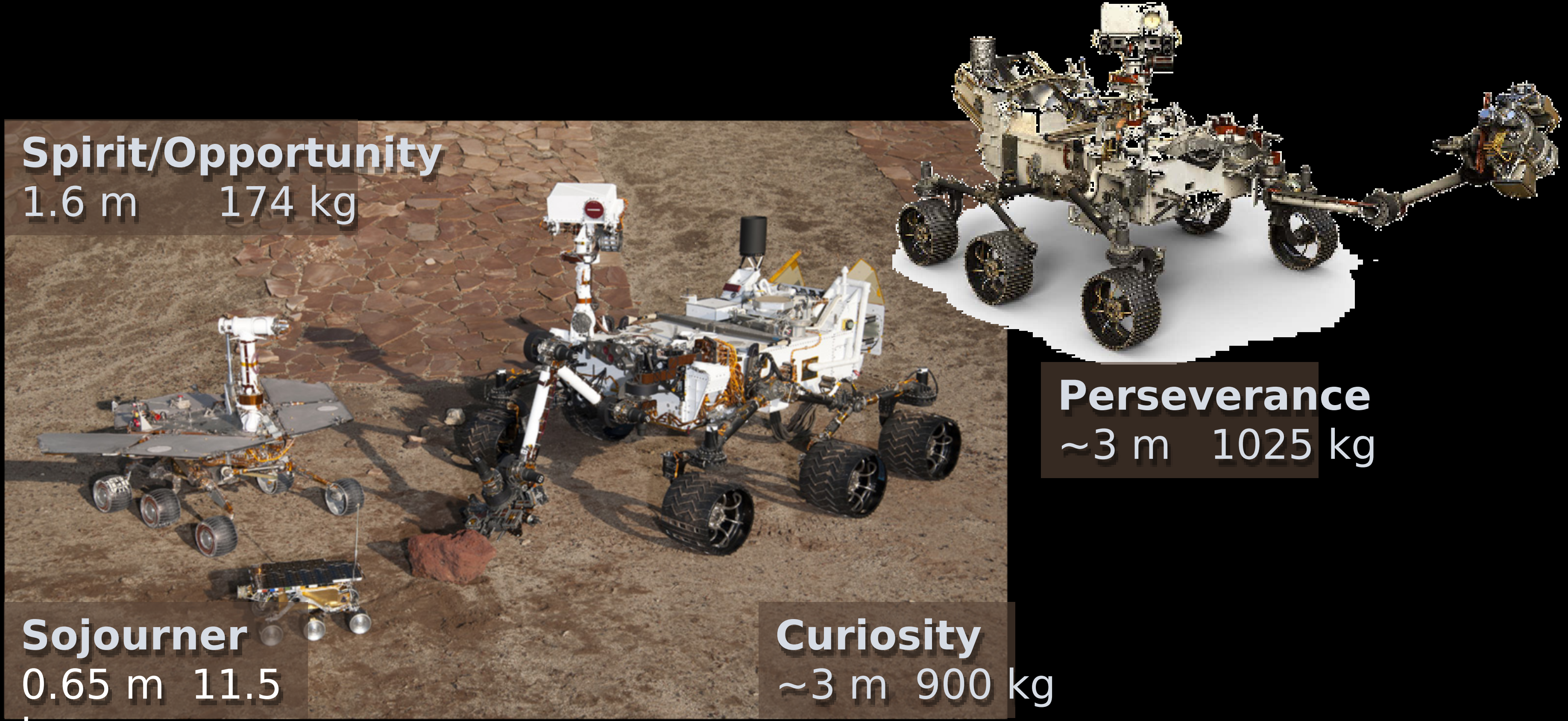
Robby (1990)


Rocky 4 (1992)


FIDO/Athena (2002)


Aerobot(2006)

Mars Flight Rovers



Spirit/Opportunity
1.6 m 174 kg

Perseverance
~3 m 1025 kg

Sojourner
0.65 m 11.5 kg

Curiosity
~3 m 900 kg

Extreme Terrain Robots

ATHLETE(2004)

Axel/DuAxel (2011)

RoboSimian (2015)

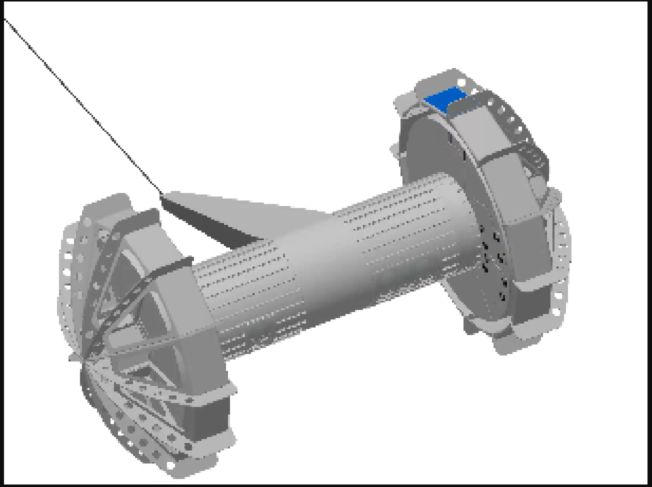
EELS(2023)

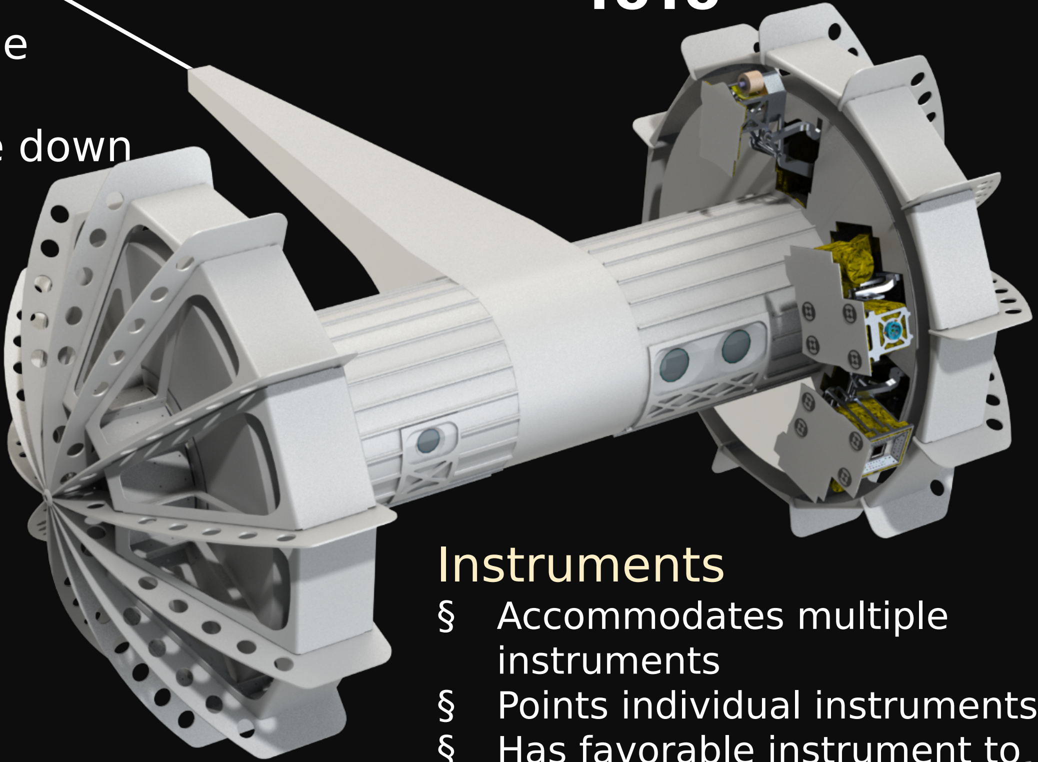
Axel: An Extreme Terrain Rover

Works like a YoYo

Mobility

- Rappels down steep terrains
- Overcomes obstacles using large grousers
- Is versatile and operates upside down
- Uses minimal actuation

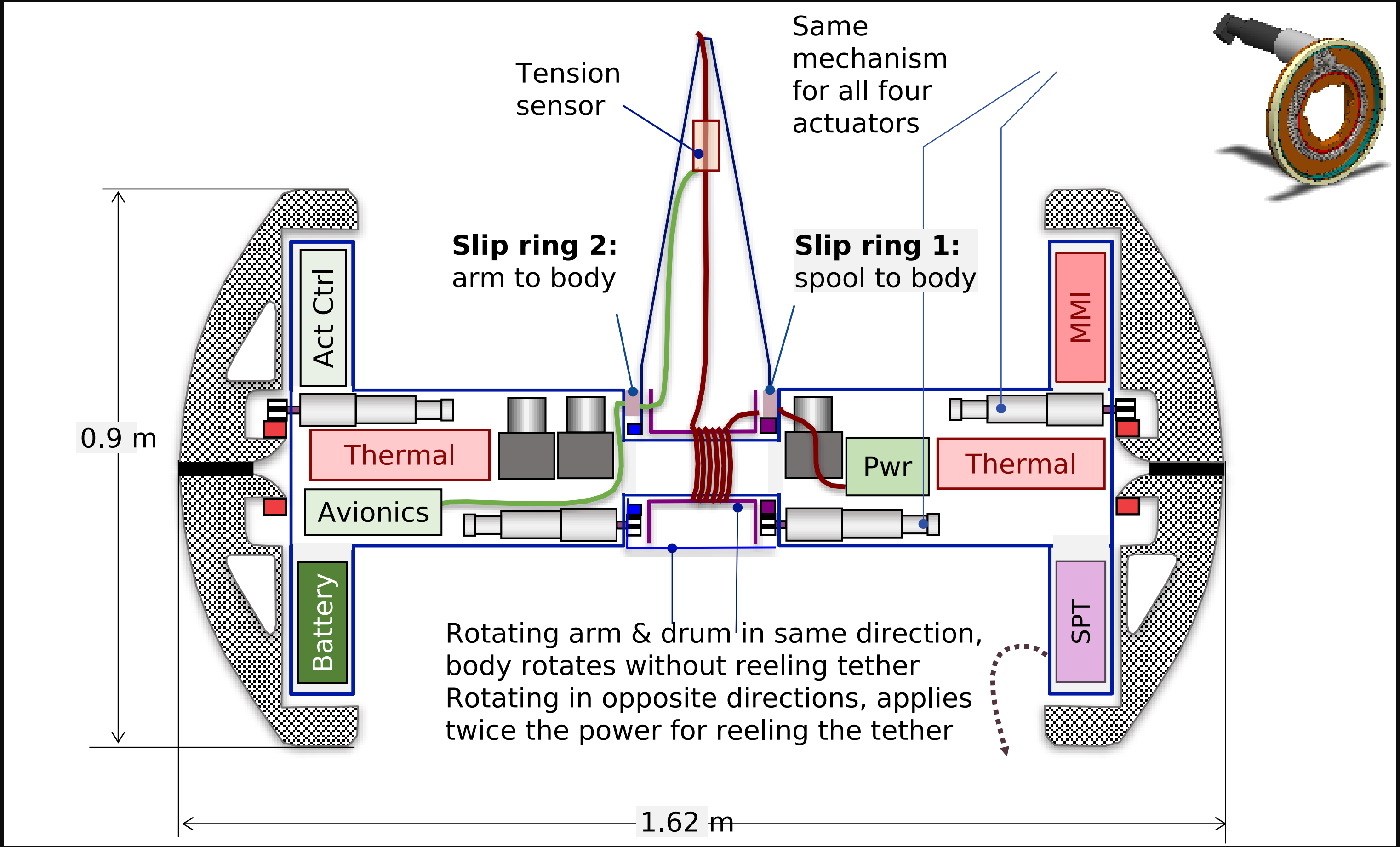




Instruments

- Accommodates multiple instruments
- Points individual instruments
- Has favorable instrument to system mass ratio

Axel: The Design



Tension sensor

Same mechanism for all four actuators

Slip ring 2: arm to body

Slip ring 1: spool to body

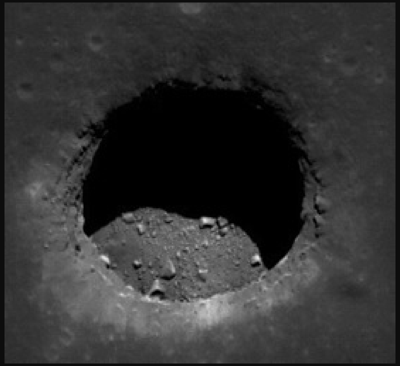
Rotating arm & drum in same direction, body rotates without reeling tether
Rotating in opposite directions, applies twice the power for reeling the tether

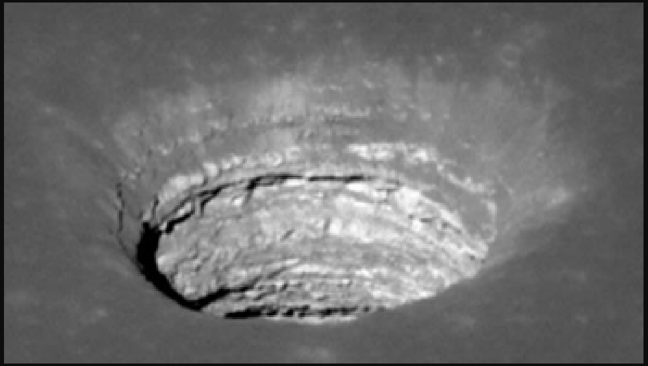
MOON DIVER A Mission Concept

Origins and Processes

- Formation of secondary planetary crusts
- Emplacement process of volcanic flows

Enabled by *robotic* access to exposed strata for in-situ measurements





Extreme Terrain Robots

Axel

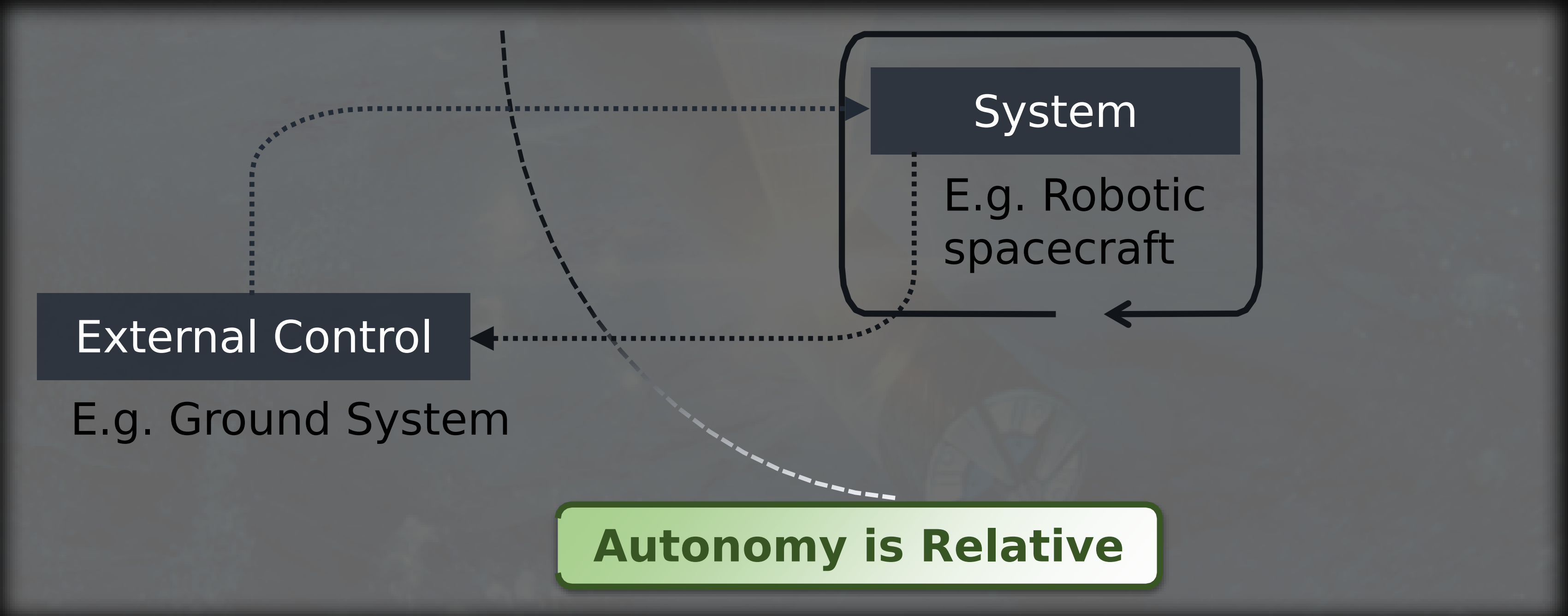
Rovers

Autonomous Explorers

What is Autonomy?

Autonomy is the ability of a system to achieve goals while operating independently of external control

NASA Autonomous Systems Taxonomy, Rev 1, 2018



System

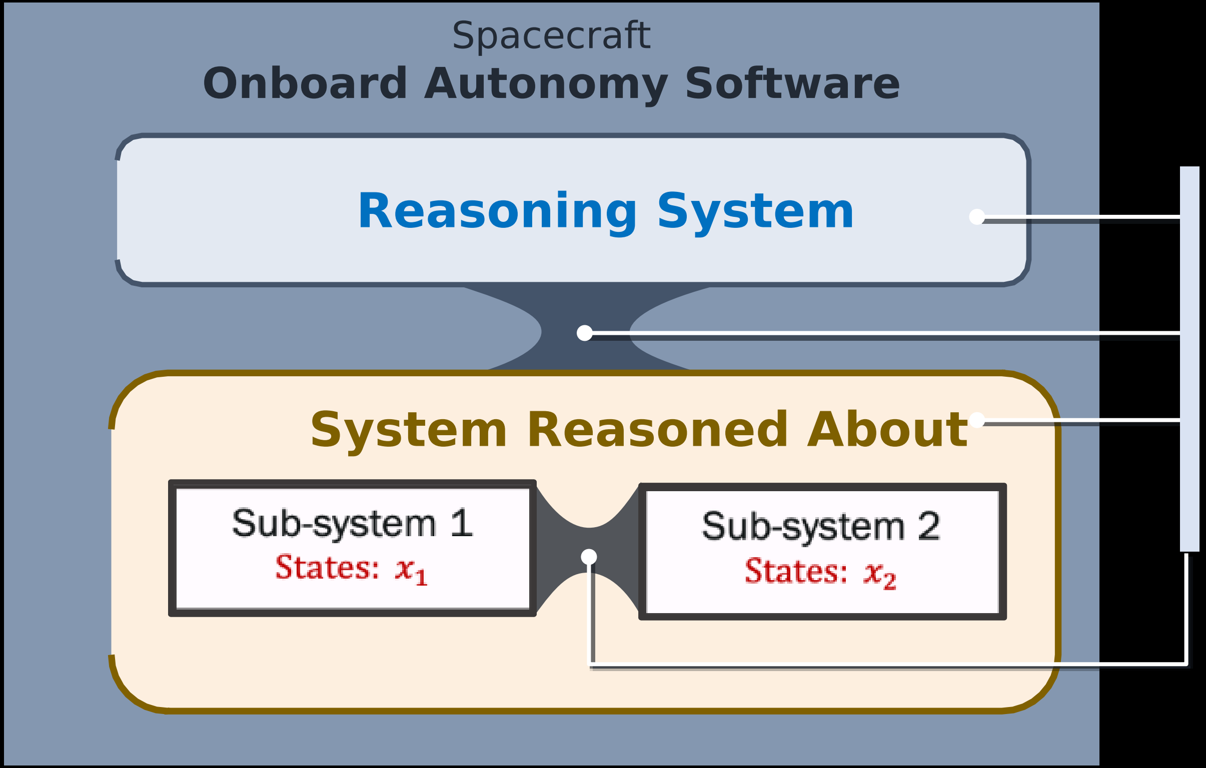
E.g. Robotic spacecraft

External Control

E.g. Ground System

Autonomy is Relative

Autonomous Spacecraft Architecture



Spacecraft

Onboard Autonomy Software

Reasoning System

System Reasoned About

Sub-system 1

States: x_1

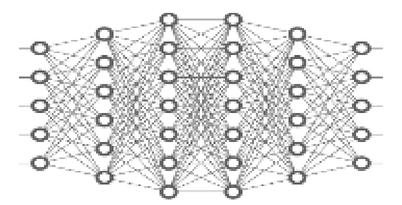
Sub-system 2

States: x_2

Modeled relations

$f(x_1, x_2) = 0$

or

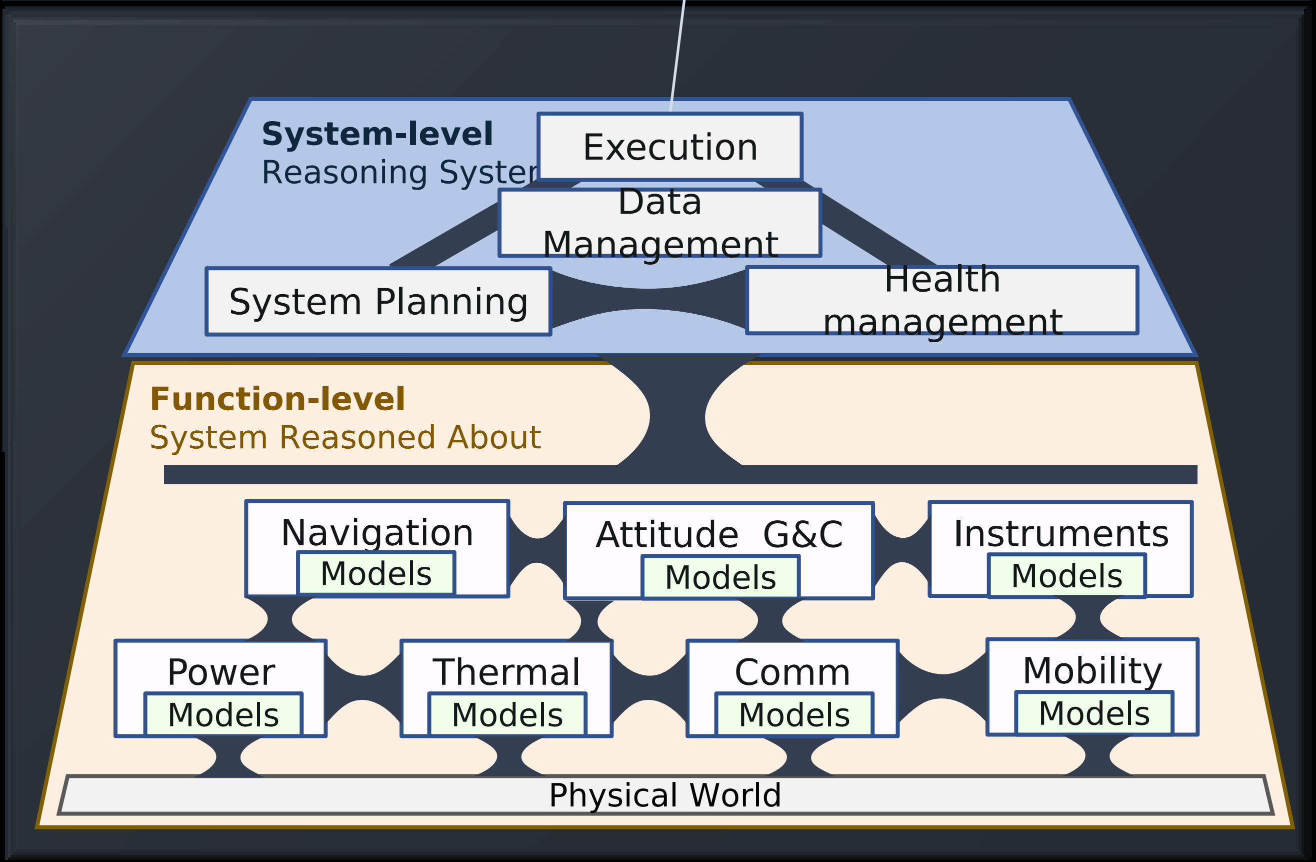


Onboard Reasoning

TECHNICAL DETAILS

DOMAIN –
STRUCTURAL VIEW

SYSTEM-LEVEL AND
FUNCTION-LEVEL



System-level
Reasoning Syste

Execution

Data Management

System Planning

Health management

Function-level
System Reasoned About

Navigation
Models

Attitude G&C
Models

Instruments
Models

Power
Models

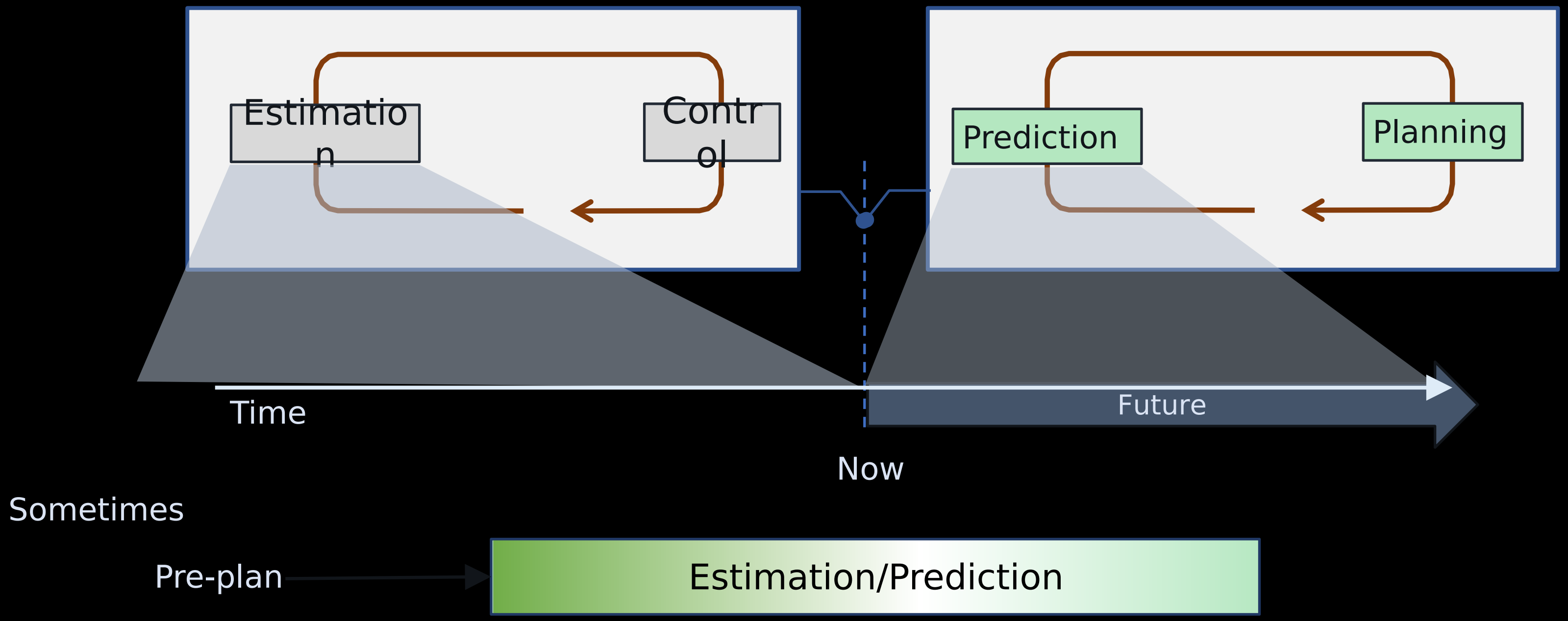
Thermal
Models

Comm
Models

Mobility
Models

Physical World

Onboard Reasoning



Estimation

Control

Prediction

Planning

Time

Future

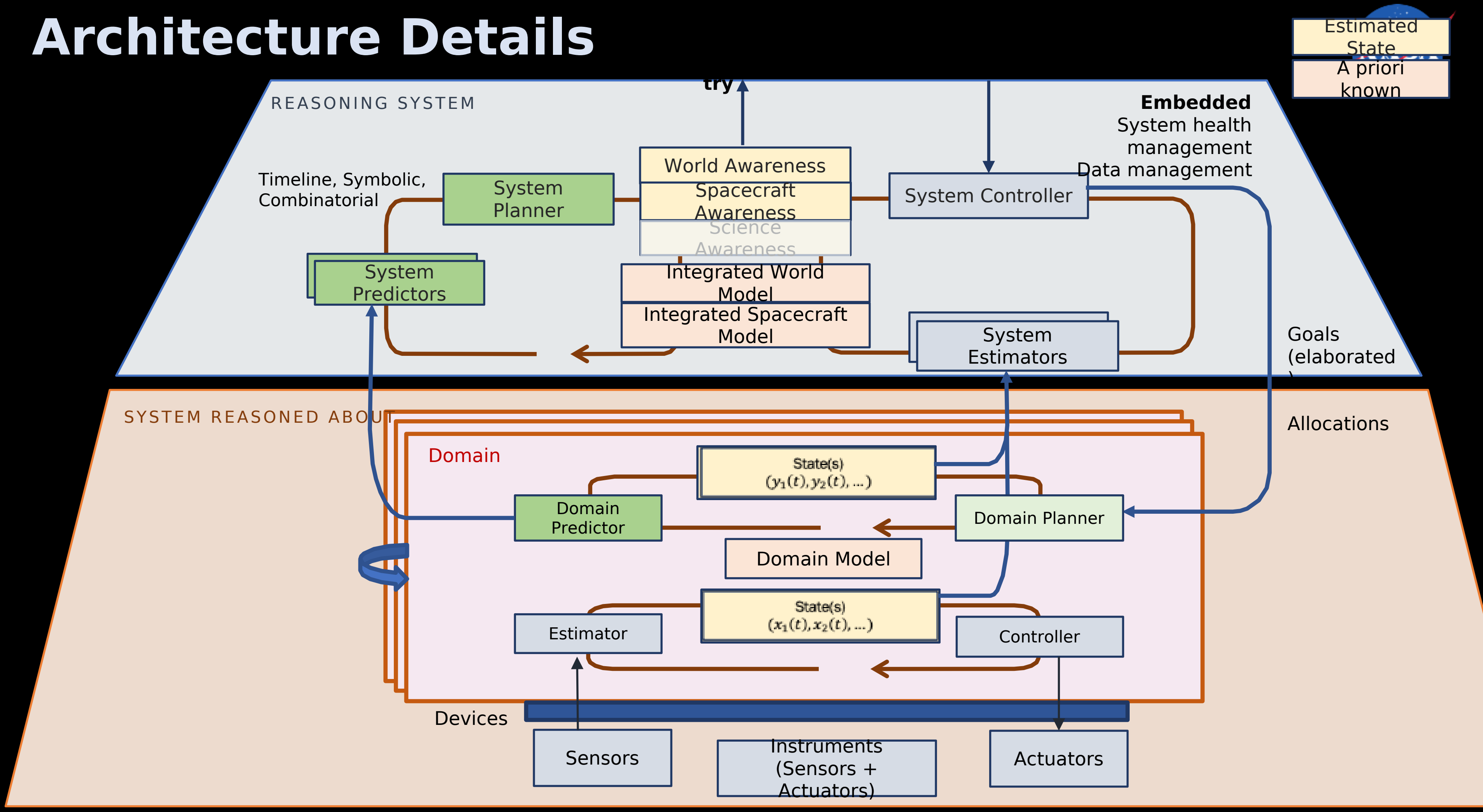
Now

Sometimes

Pre-plan

Estimation/Prediction

Architecture Details



Estimated State

A priori known

try

REASONING SYSTEM

Embedded
System health management
Data management

Timeline, Symbolic, Combinatorial

System Planner

World Awareness

Spacecraft Awareness

Science Awareness

System Controller

System Predictors

Integrated World Model

Integrated Spacecraft Model

System Estimators

Goals (elaborated)

Allocations

SYSTEM REASONED ABOUT

Domain

State(s) $(y_1(t), y_2(t), \ldots)$

Domain Predictor

Domain Planner

Domain Model

State(s) $(x_1(t), x_2(t), \ldots)$

Estimator

Controller

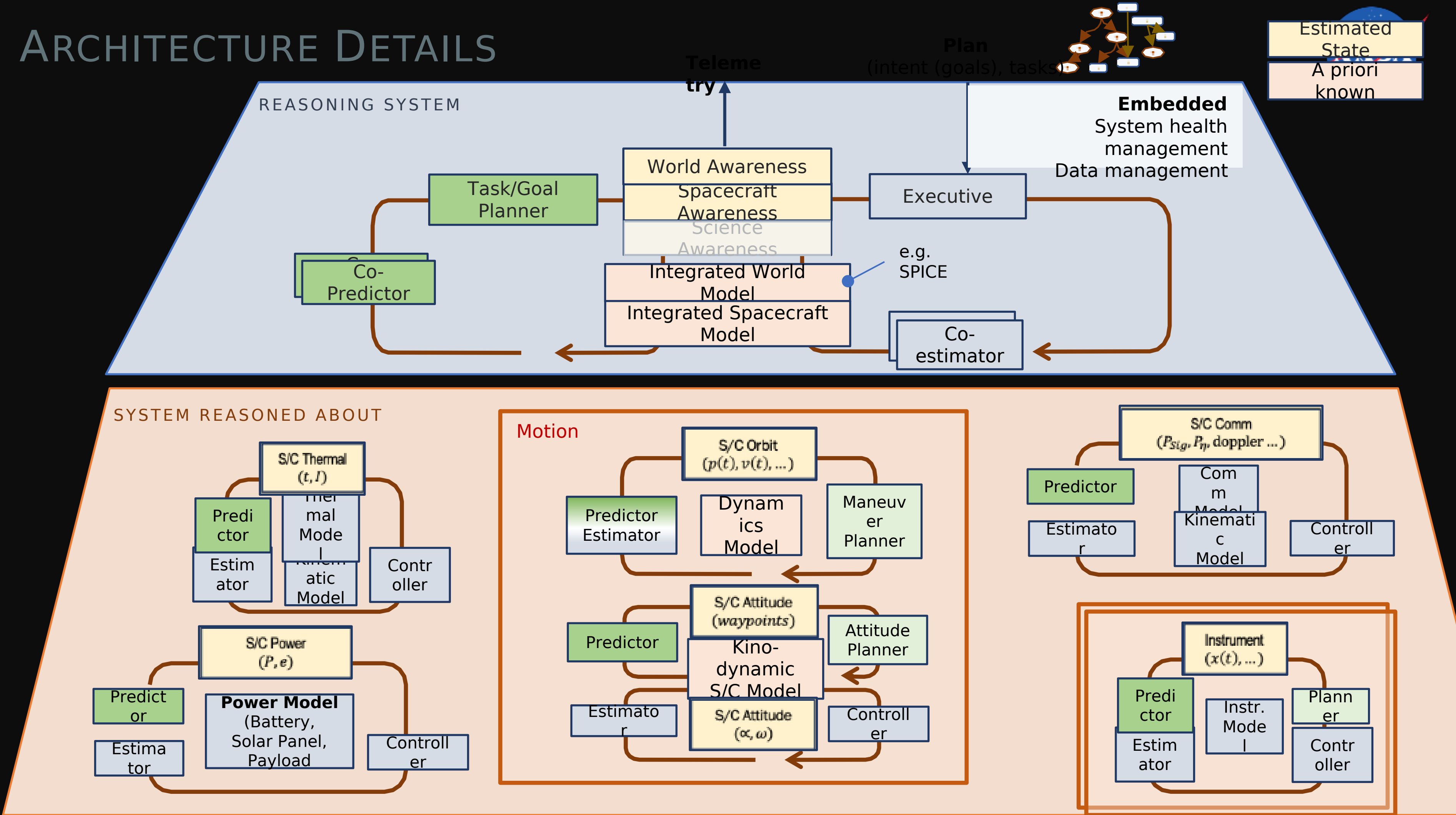
Devices

Sensors

Instruments (Sensors + Actuators)

Actuators

ARCHITECTURE DETAILS



Estimated State

A priori known

Telemetry

Plan
(intent (goals), tasks)

REASONING SYSTEM

Embedded
System health management
Data management

World Awareness

Spacecraft Awareness

Science Awareness

Task/Goal Planner

Executive

Co-Predictor

Integrated World Model

Integrated Spacecraft Model

e.g. SPICE

Co-estimator

SYSTEM REASONED ABOUT

S/C Thermal
(t, I)

Predictor

Thermal Model

Estimator

Kinematic Model

Controller

S/C Power
(P, e)

Predictor

Estimator

Power Model
(Battery, Solar Panel, Payload

Controller

Motion

S/C Orbit
$(p(t), v(t), \dots)$

Predictor Estimator

Dynamics Model

Maneuver Planner

S/C Attitude
$(waypoints)$

Predictor

Kino-dynamic S/C Model

Attitude Planner

Estimator

S/C Attitude
(α, ω)

Controller

S/C Comm
$(P_{sig}, P_n, \text{doppler} \dots)$

Predictor

Comm Model

Estimator

Kinematic Model

Controller

Instrument
$(x(t), \dots)$

Predictor

Estimator

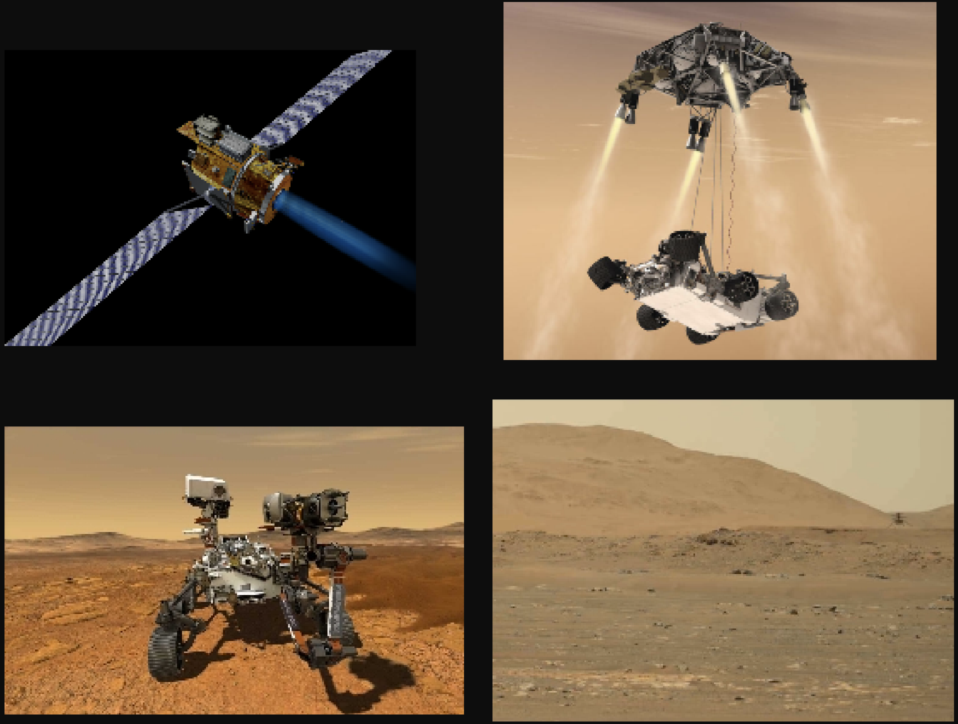
Instr. Model

Planner

Controller

Recently Flown Autonomous Capabilities

- **Deep space navigatio**
- **Entry, descent and landing**
- **Surface mobility**
- **Above-surface mobility**



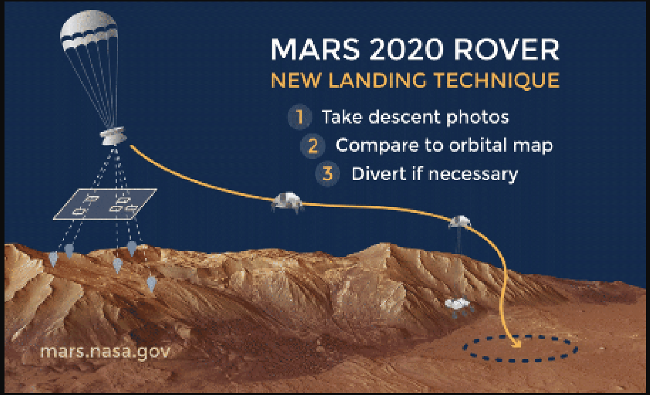
Spacecraft Control
Entry, Descent and Landing

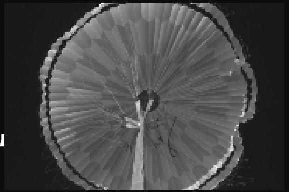
Flight Deployed

- **2003 Mars Exploration Rover:** descent imagery used to estimate and control horizontal velocity
- **2011 Mars Science Laboratory:** closed-loop guidance, navigation and control (GNC) to guide large lander to a soft touchdown
- **2020 Perseverance Mission:** closed-loop GNC with terrain-relative navigation using orbital maps with divert to a safe landing site, if necessary

Research

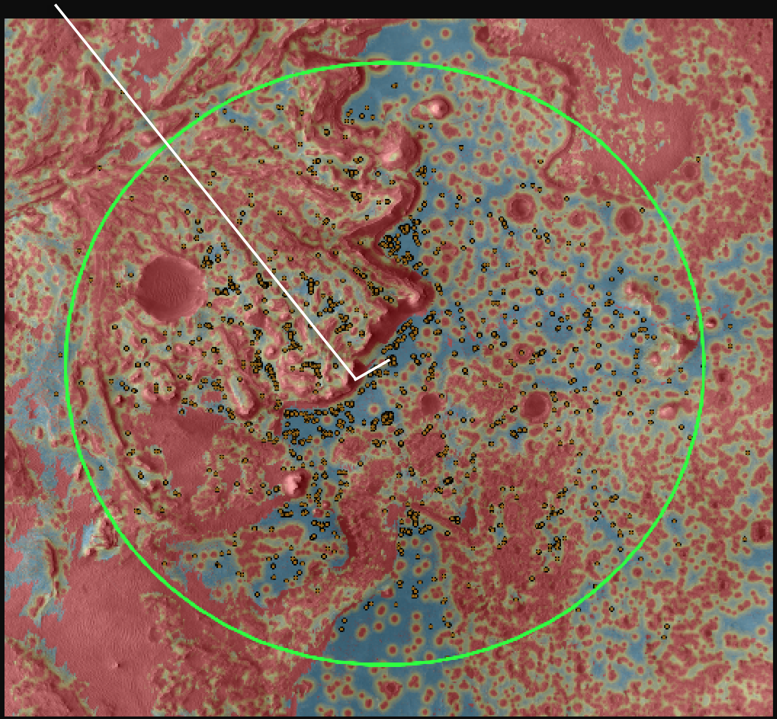
- **Pin-point landing using TRN (ocean worlds, landing)**
- **Sensors and algorithms for real-time detection of hazard**

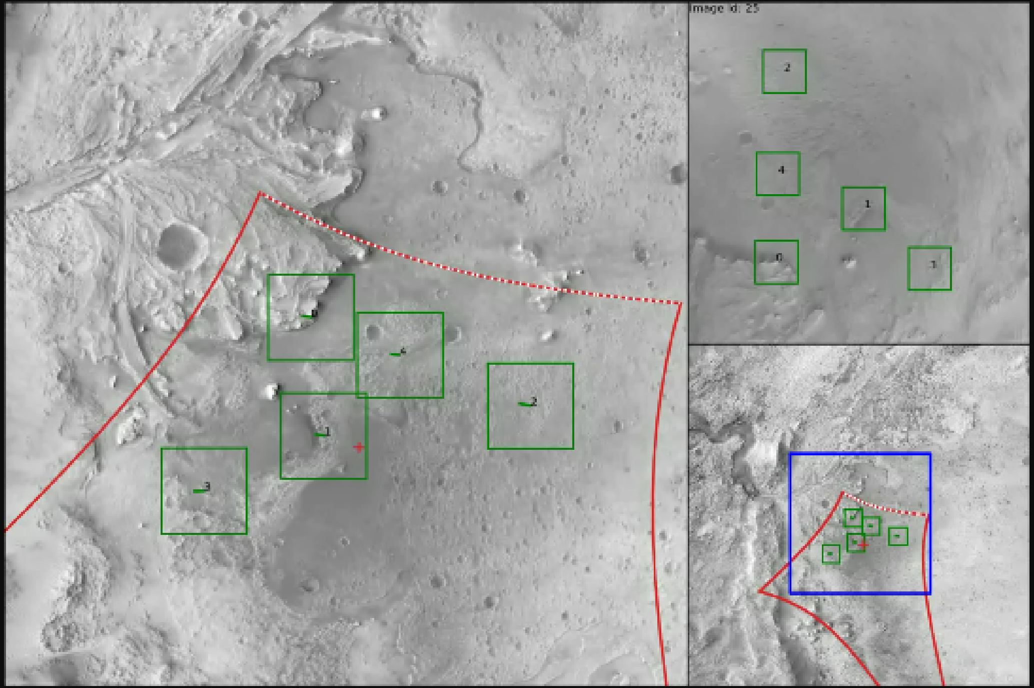




Year	Mission	Landing Ellipse
2003	Mars Exploration Rover	150 km × 20 km
2011	Mars Science Lab	20 km × 7 km

Jezero Cater on Mars

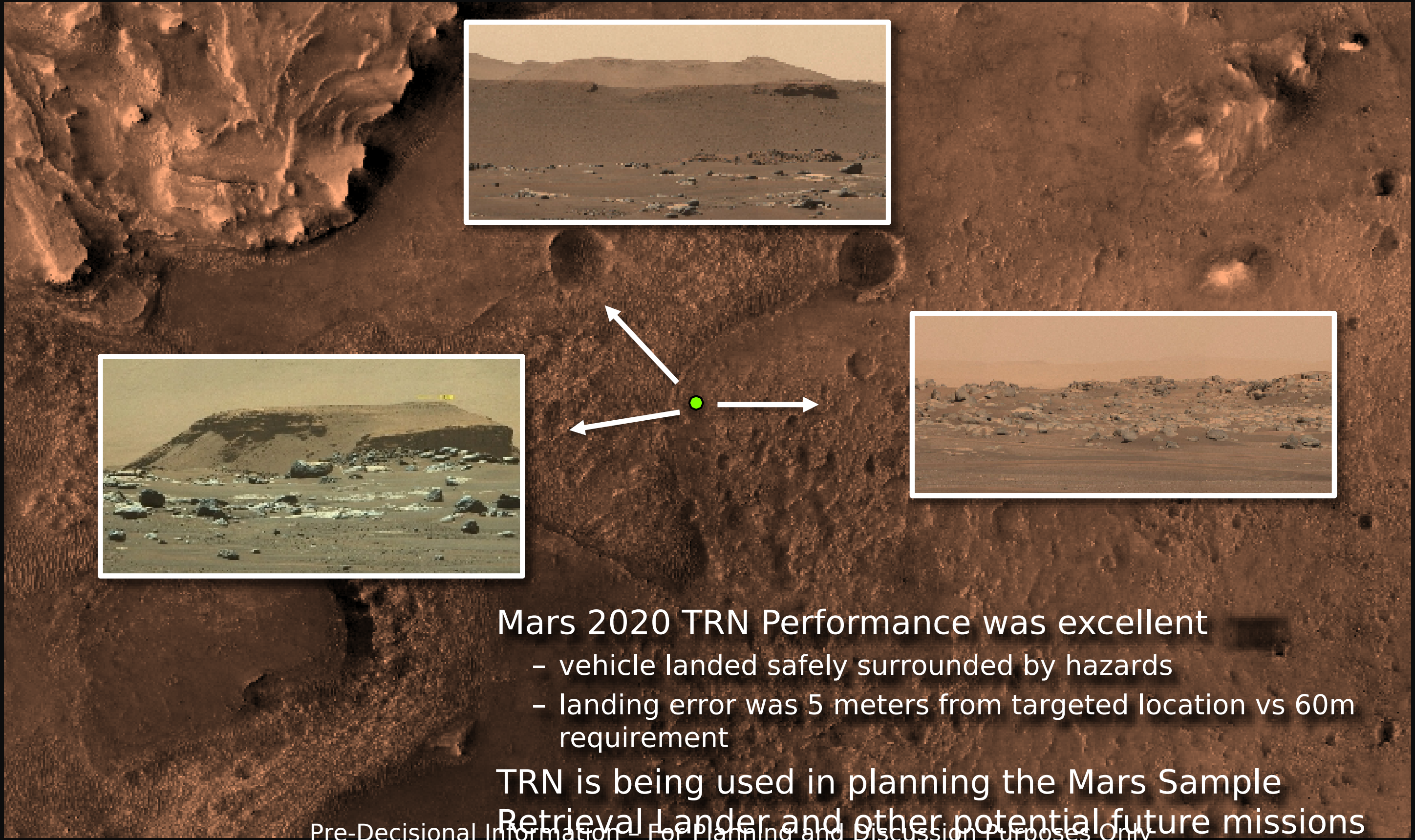




☐ Landing Ellipse
🟧 Landing Hazards

Credit: Andrew Johnson

Mars 2020 TRN Summary



Mars 2020 TRN Performance was excellent

- vehicle landed safely surrounded by hazards
- landing error was 5 meters from targeted location vs 60m requirement

TRN is being used in planning the Mars Sample Retrieval Lander and other potential future missions

Credit: Andrew Johnson

Robot Control

Surface Mobility and Navigation

Flight Deployed

- **1996 Mars Pathfinder:** obstacle avoidance w/ structured light
- **2003 Mars Exploration Rover:** obstacle avoidance with stereo vision; pose estimation and slip detection with visual odometry; visual target tracking
- **2011 Curiosity Rover:** faster visual odometry
- **2020 Perseverance Rover:** thinking while driving, capability to traverse more complicated terrain

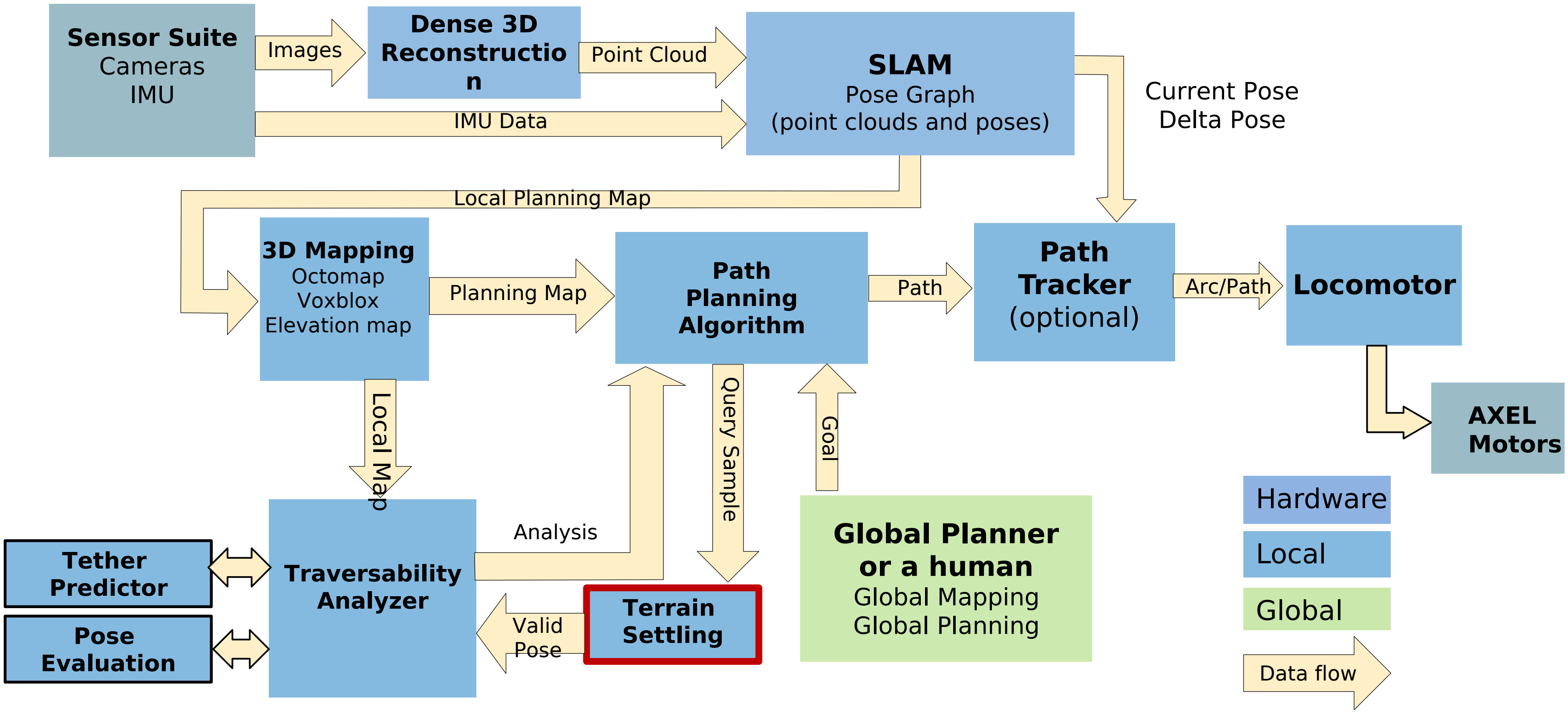
Research

- Long-duration, high-speed, energy-efficient autonomous navigation and localization for lunar and martian missions
- Traversability analysis, on-board terrain classification, motion planning under uncertainty
- Extreme-terrain and microgravity mobility and navigation

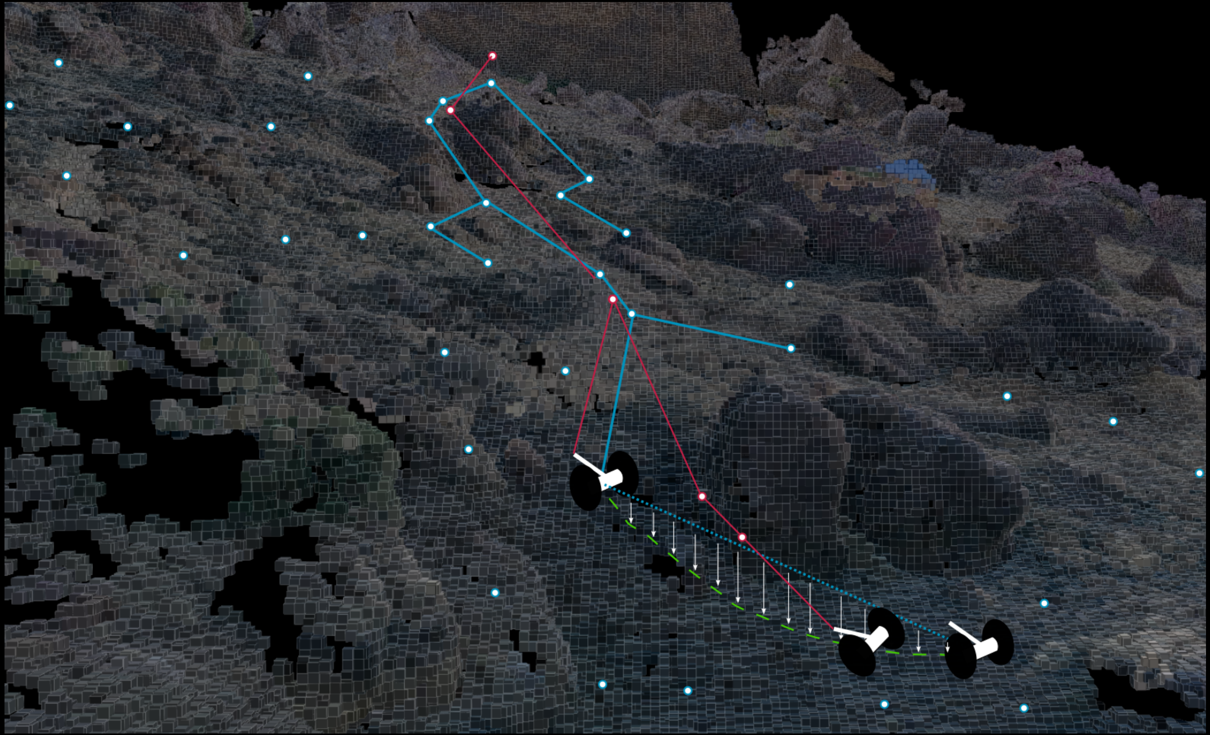
Distance record: 245.8 m
as of Sol 341 (Feb 4, 2022)

Surface Navigation Research

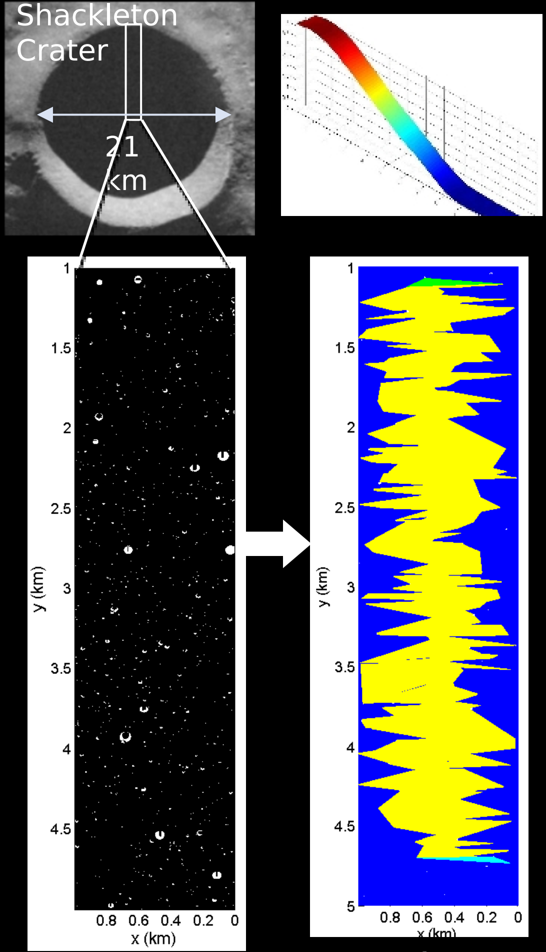
Tethered Navigation



Tethered Navigation



M. Paton et al, “Navigation on the Line: Traversability Analysis and Path Planning for Extreme-Terrain Rappelling Rovers,” IROS 2020
NASA/JPL-Caltech, University of Oxford

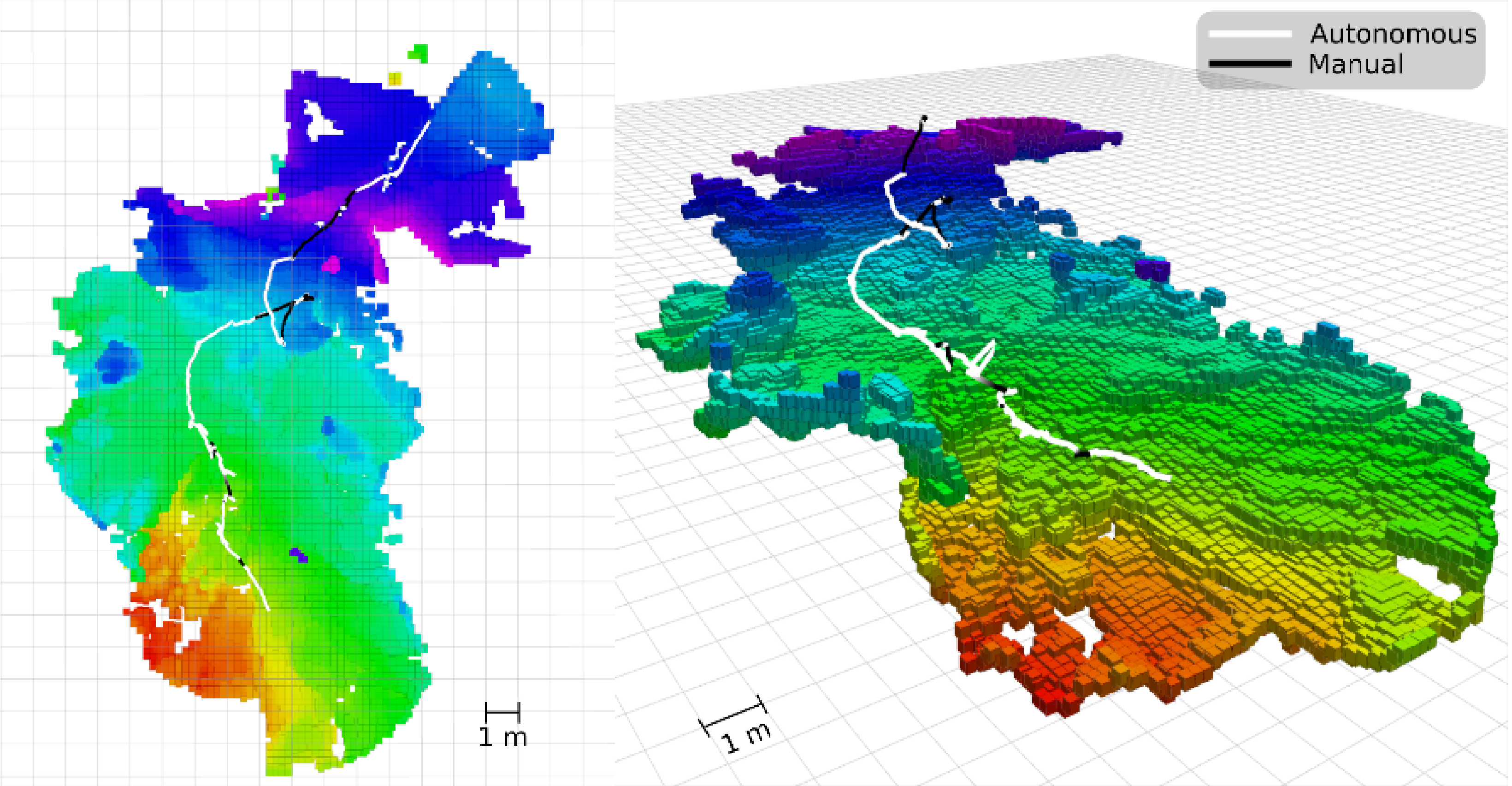


All geometric hazards

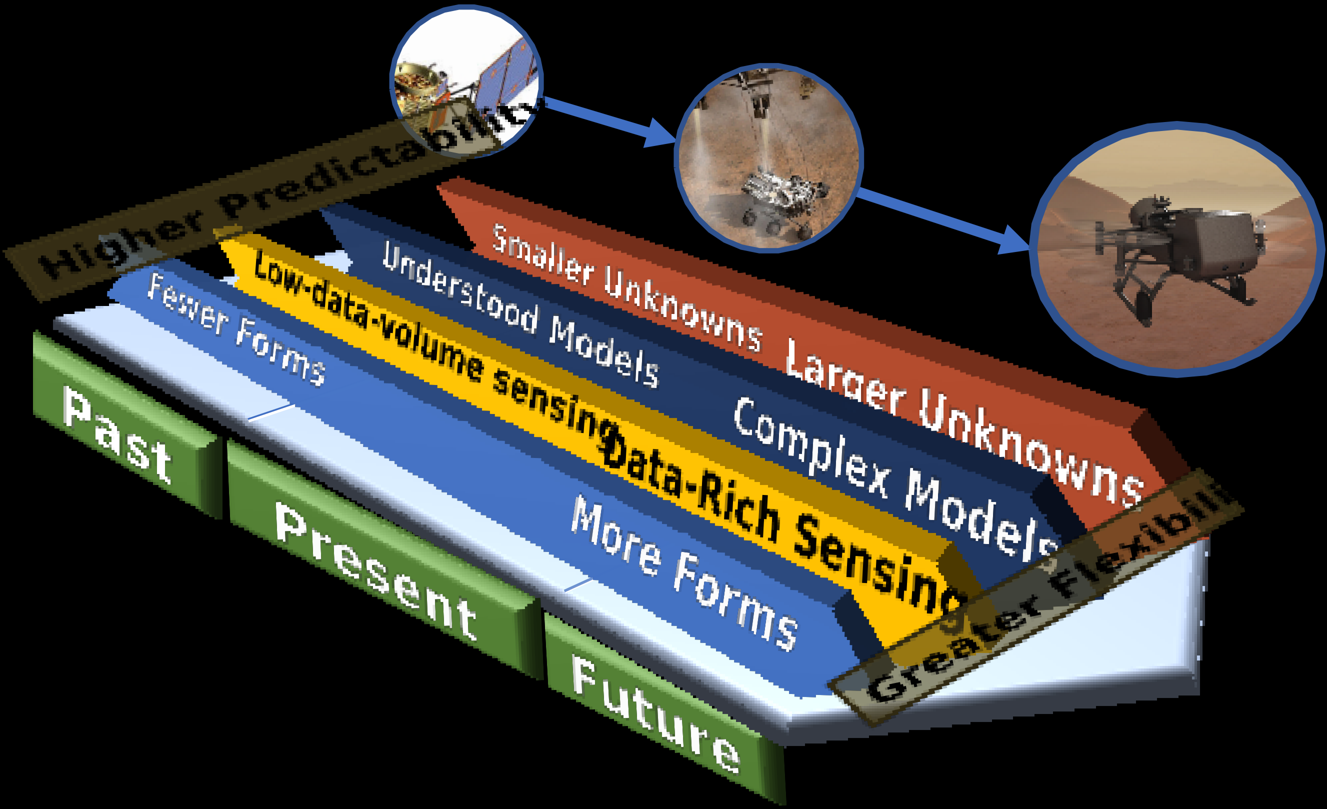
One of many sleeves (corridors) for tethered

M. Tanner, P. Abad-Manterola, J. Burdick, Caltech, ICRA 2012

Field Test Results from Anchor Prediction



Why Do We Need Autonomy?



Examples

Unknowns
- Terrains
- Materials
- Contact

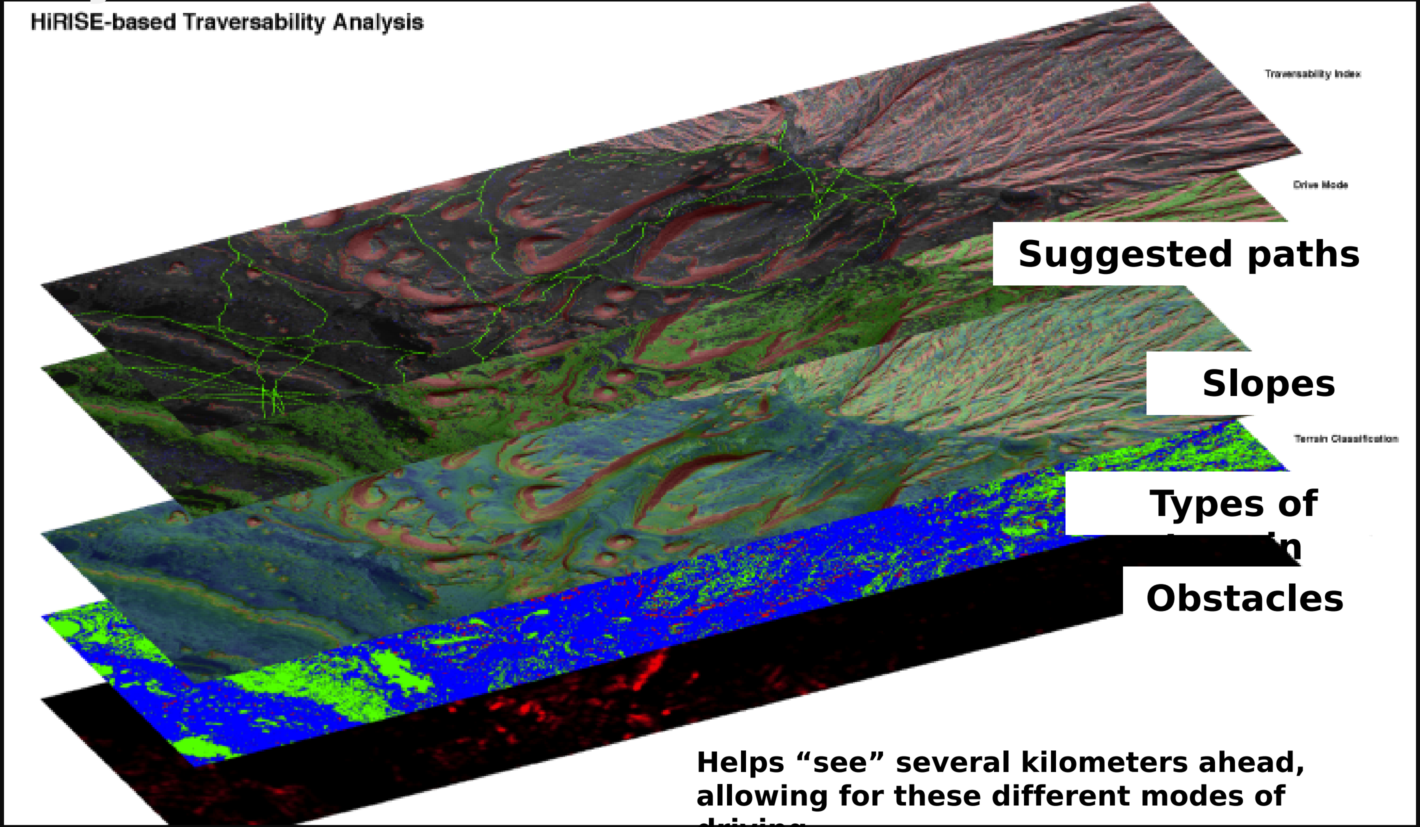
Models
- Terra-mechanics
- Weather
- Physical contact

Sensing
- Visual
- 3D mapping
- Traversability
- Object recognition

Forms
- Rovers
- Balloons
- Arms
- Melting probes

Nesnas, I.A., Fesq, L.M. & Volpe, R.A. **Autonomy for Space Robots: Past, Present, and Future**. *Current Robot Report* **2**. (2021).

Traverse Planning in Orbital Imagery



Suggested paths

Slopes

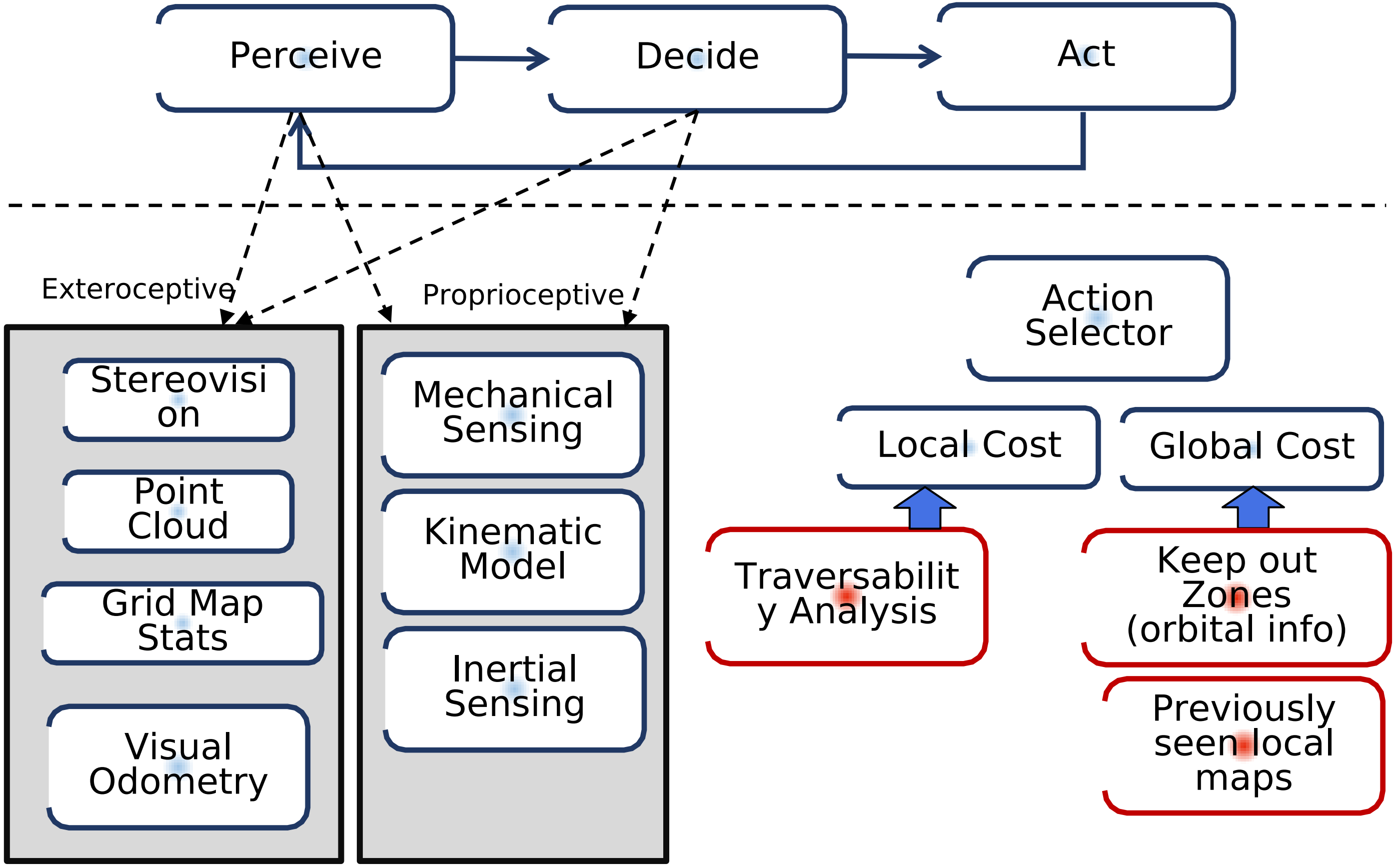
Types of [illegible]n

Obstacles

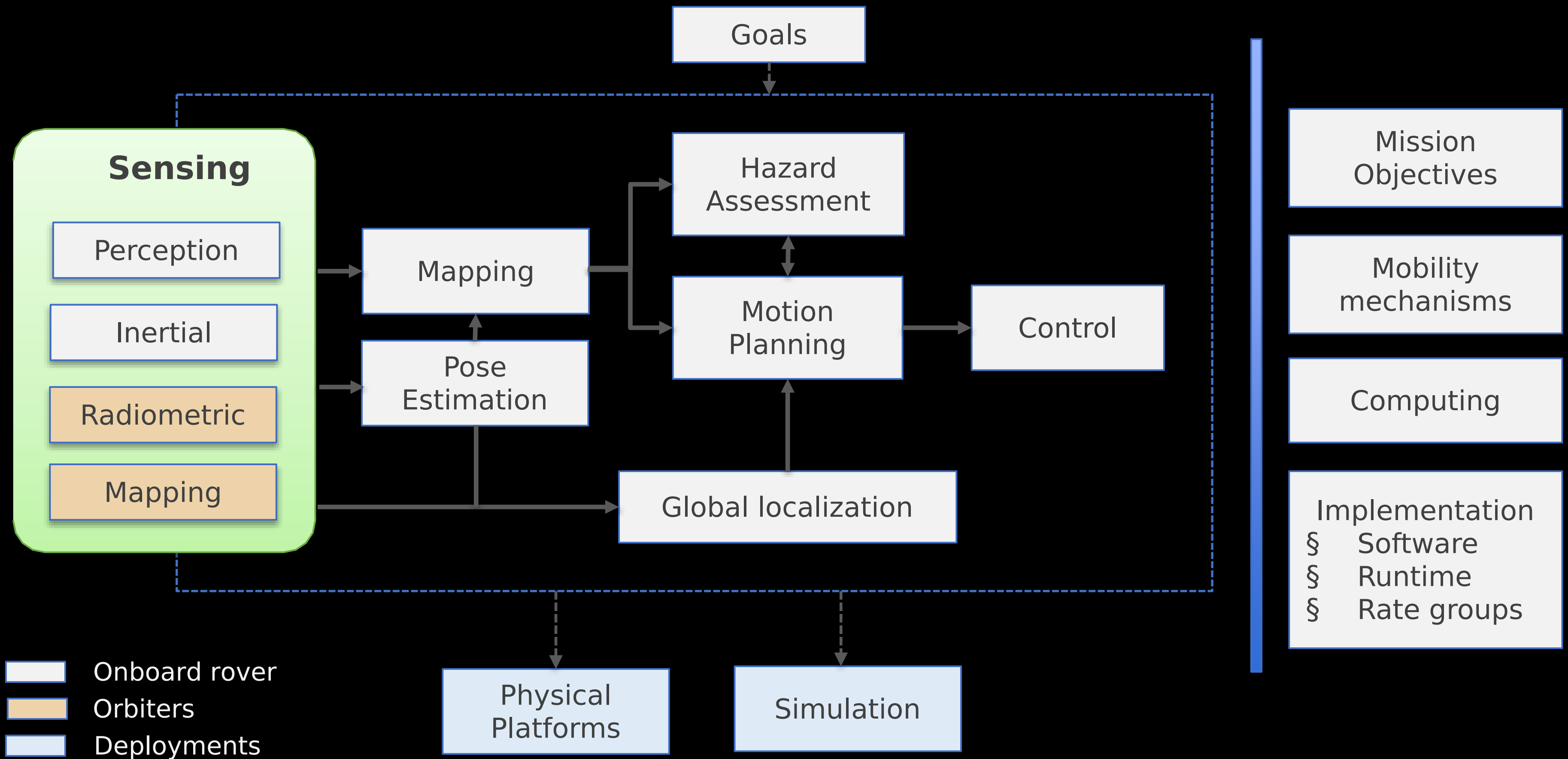
Helps “see” several kilometers ahead, allowing for these different modes of driving.

Credit: Mark Maimone

Function-level Autonomy: Onboard Navigation



Planetary Mobility Overview



Goals

Sensing

Perception

Inertial

Radiometric

Mapping

Mapping

Pose Estimation

Hazard Assessment

Motion Planning

Control

Global localization

Physical Platforms

Simulation

Mission Objectives

Mobility mechanisms

Computing

Implementation

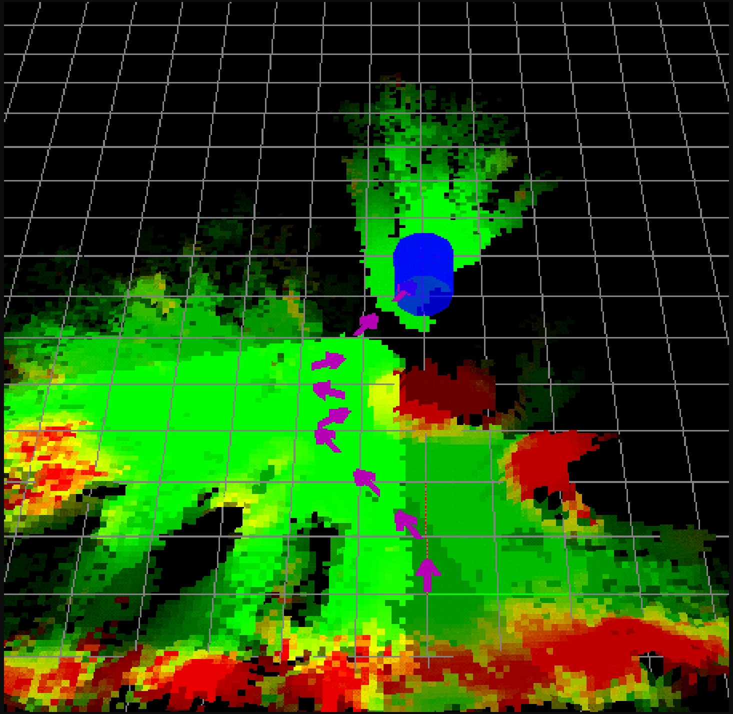
- Software
- Runtime
- Rate groups

⬜ Onboard rover

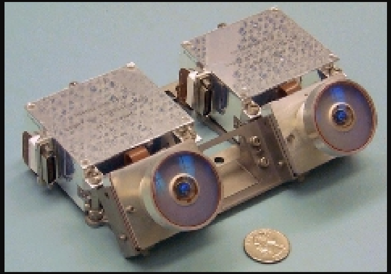
🟫 Orbiters

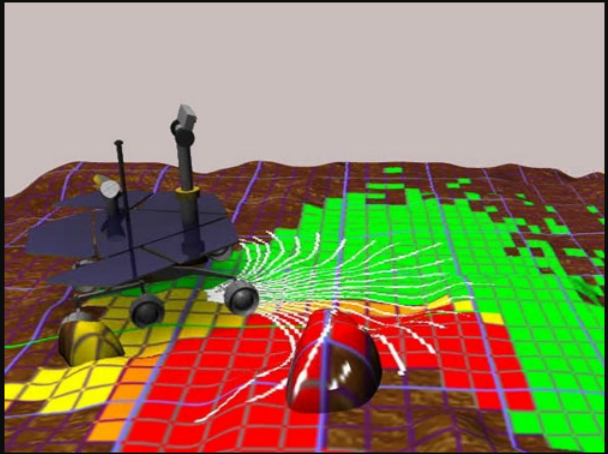
🟦 Deployments

Terrain Analysis and Hazard Detection



Credit: CLARAty - JPL/Carnegie Mellon – C Urmson, et al.

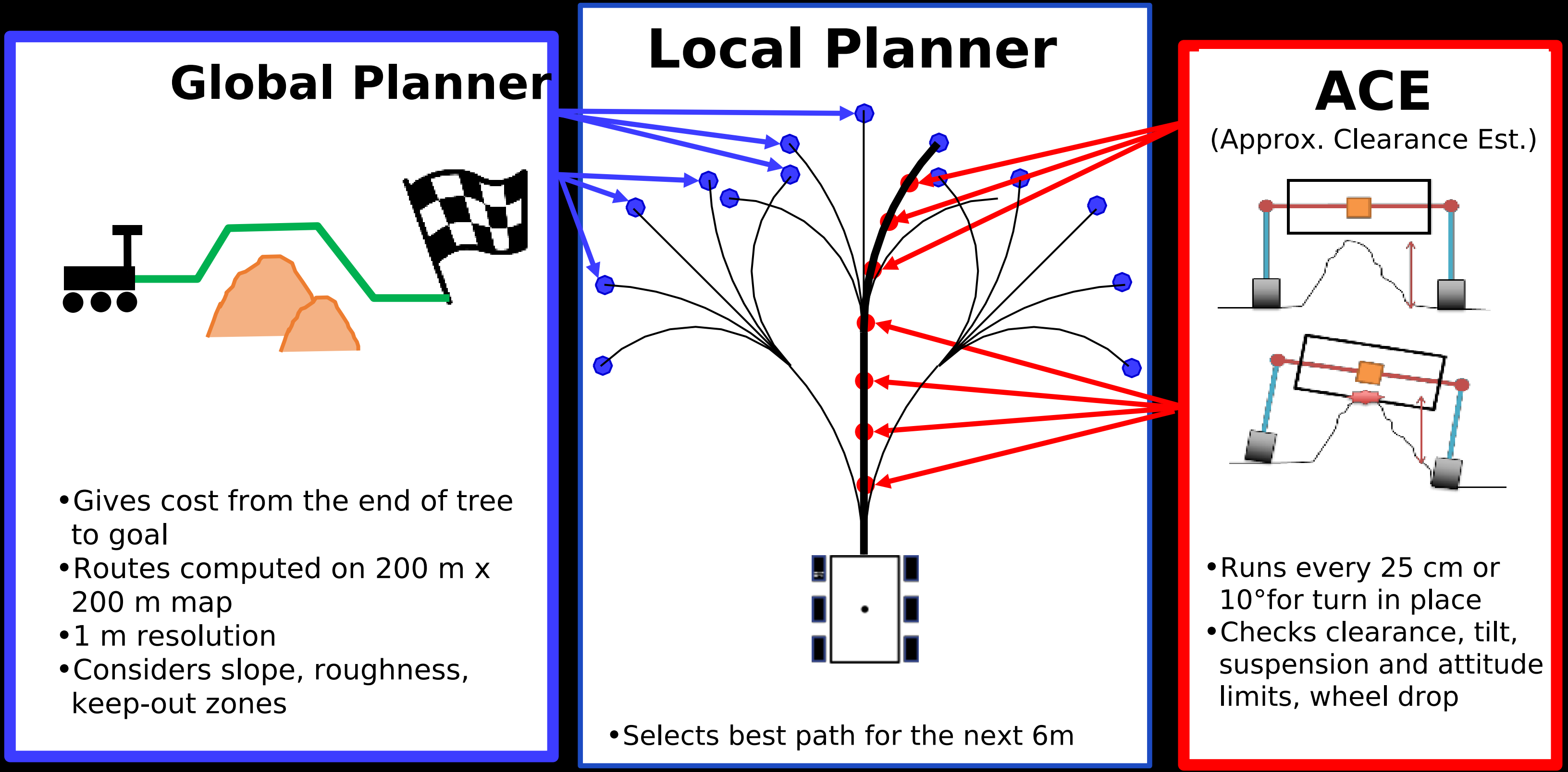




Credit: JPL/GESTALT navigation – Mark Maimone

- Rover control
- Rover navigation
- Path planning with continuous replanning
- Terrain Traversability analysis
- Multi-stereo data fusion
- Visual odometry
- Stereovision
- Inertial sensing and estimation
- Manipulation (mast)
- Locomotion
- Mechanism model
- Rover/mast kinematics
- Trajectory generation
- Servo (PID control)
- I/O control

Perseverance Enhanced Navigation



Global Planner

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

Local Planner

- Selects best path for the next 6m

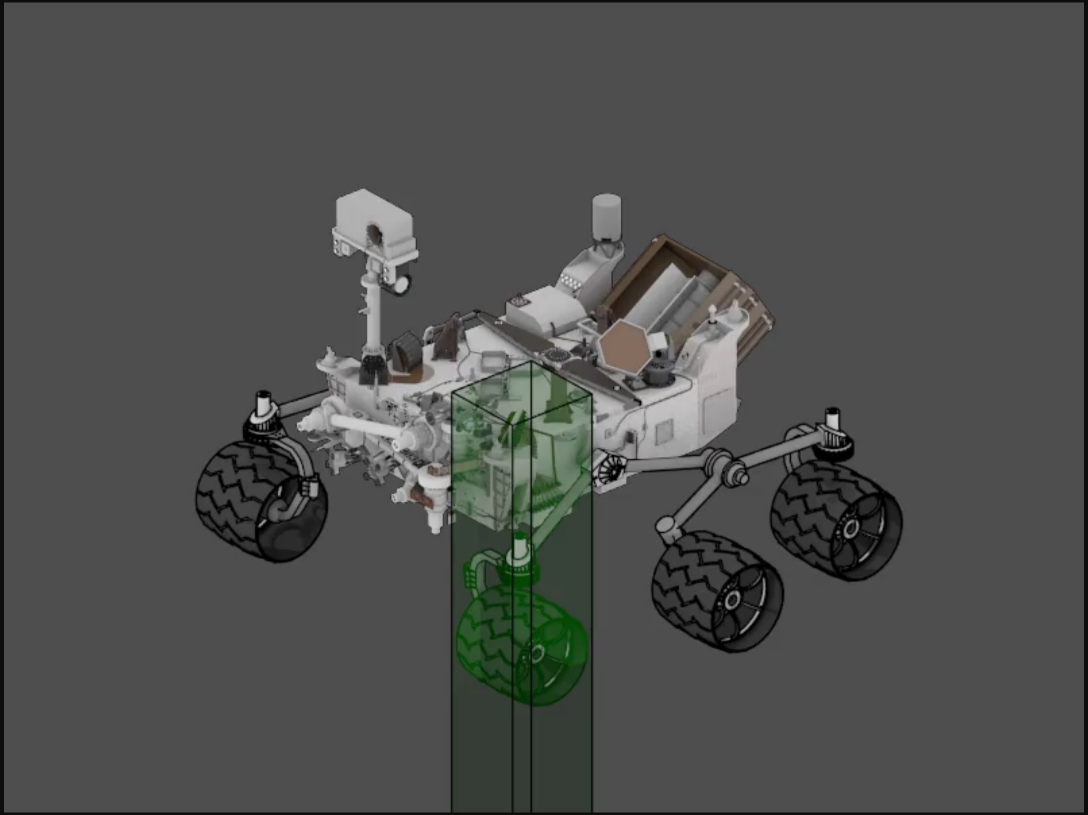
ACE

(Approx. Clearance Est.)

- Runs every 25 cm or 10°for turn in place
- Checks clearance, tilt, suspension and attitude limits, wheel drop

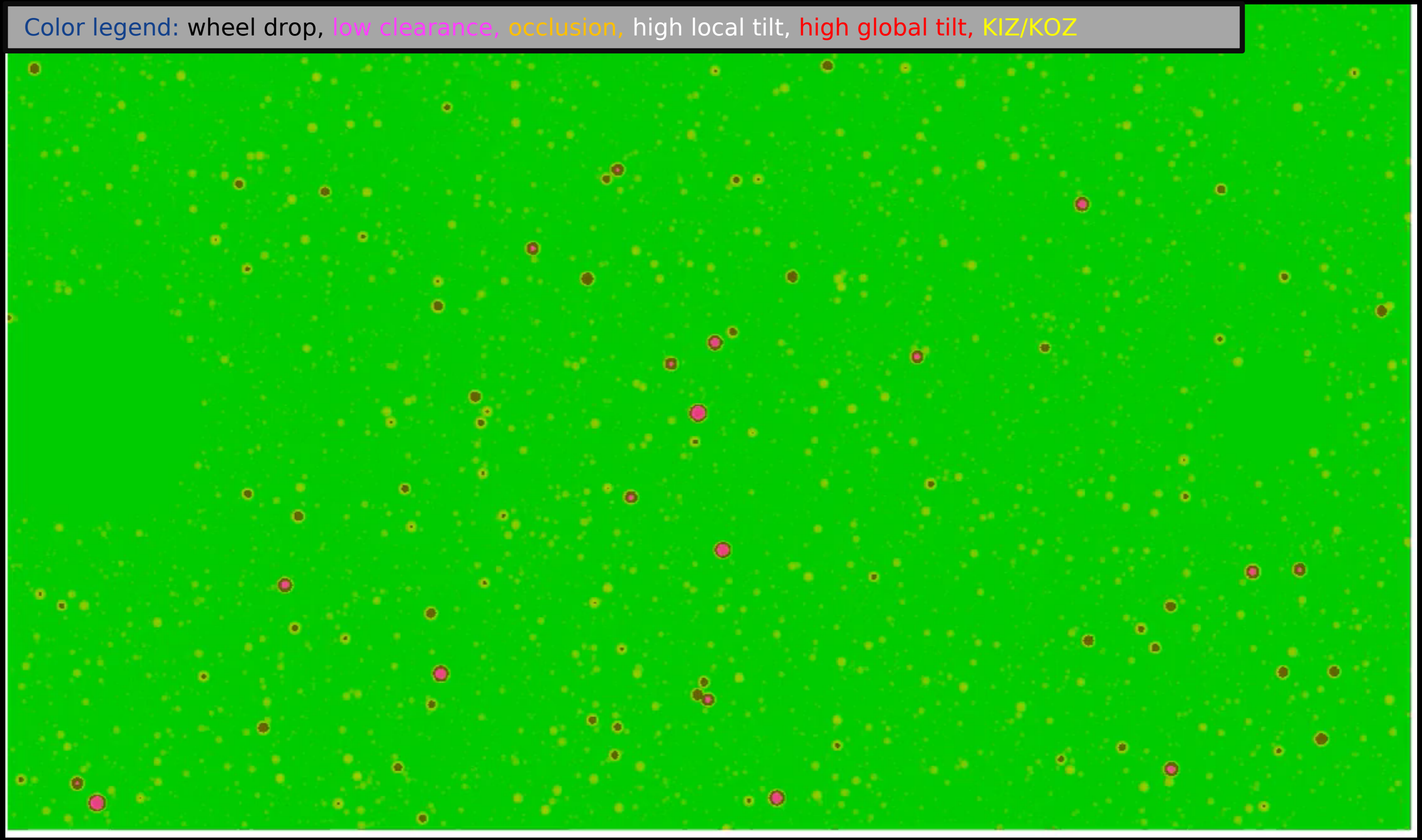
Credit: Olivier Toupet, Hiro Ono, Michael McHenry, Tyler Del Sesto

ACE: Approximate Clearance Evaluation



Credit: Guillaume Matheron, Olivier Toupet, Tyler Del Sesto, Hiro Ono, Michael McHenry

Monte Carlo Simulations



Credit: Guillaume Matheron, Olivier Toupet, Tyler Del Sesto, Hiro Ono, Michael McHenry

Perseverance Autonomous Navigation: Sol 122

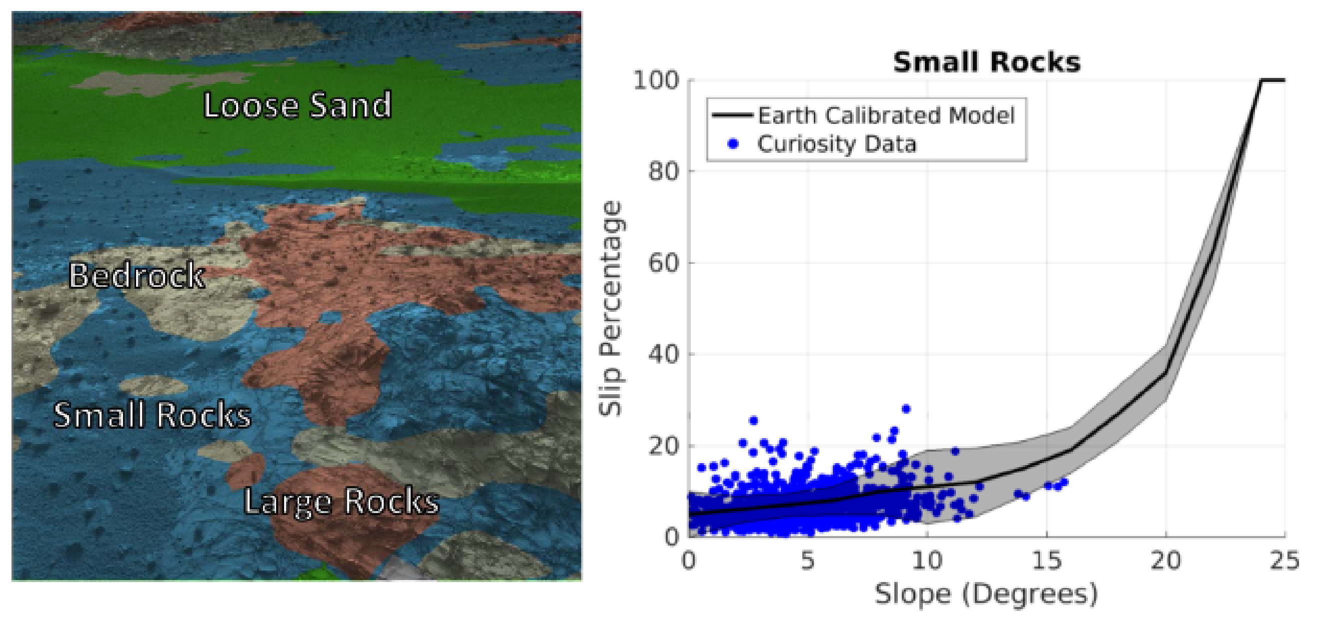
Perseverance Autonomous Navigation

Distance record: 245.8 m
as of Sol 341
(Feb 4, 2022)

Credit:
Olivier Toupet
Hiro Ono
Tyler del Sesto
Michael McHenry
Mark Maimone,
Josh Vander
Hook

Non-Geometric Hazard Assessment

- Machine-learning-Based terrain classification
- Correlating thermal inertia and slip

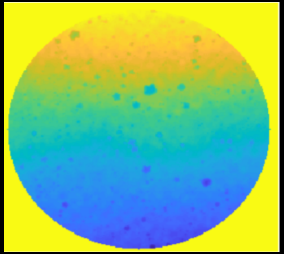


Rothrock, B., Kennedy, R., Cunningham, C., Papon, J., Heverly, M., & Ono, M. (2016). Spoc: Deep learning-based terrain classification for mars rover missions. In *AIAA SPACE 2016* (p. 5539).
Cunningham, C., Nesnas, I. A., & Whittaker, W. L. (2019). Improving slip prediction on mars using thermal inertia measurements. *Autonomous Robots*, *43*(2), 503-521.

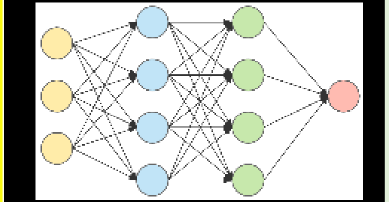
Adaptive Tree Searches

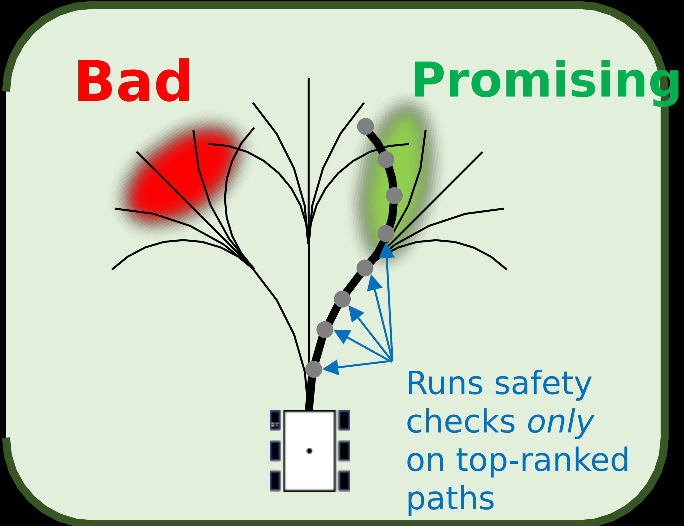
- Machine-learning-based initial terrain assessment to bias search
- Model-based traversability verification

Heightmap



Deep learning

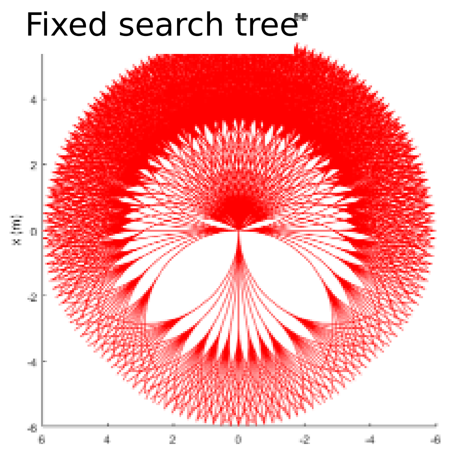




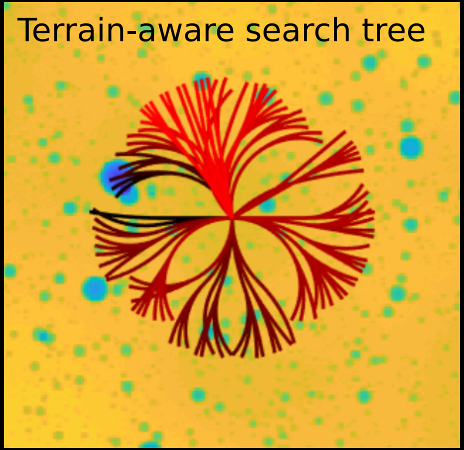
Bad

Promising

Runs safety checks *only* on top-ranked paths



Fixed search tree

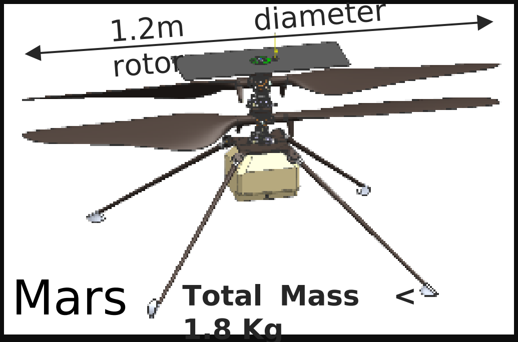


Terrain-aware search tree

N. Abcouwer et al., "Machine Learning Based Path Planning for Improved Rover Navigation," 2021 IEEE Aerospace Conference (50100), 2021, pp. 1-9, doi: 10.1109/AERO50100.2021.9438337.

Robot Control

Above-Surface Mobility: Rotorcrafts and Balloons

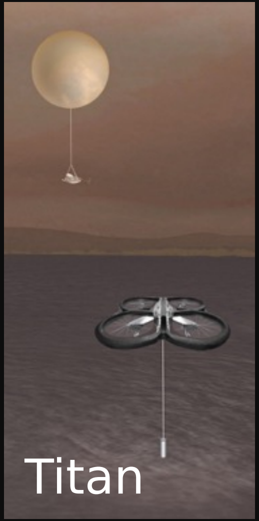


Flight Deployed

- **2020 Ingenuity Mars Helicopter (tech demo):** completed 55 flights with a maximum per flight lateral distance of 704 m and ~1 hour and 35 minutes of flying time. Flew a total of 12 km.

Research

- **Mars Helicopter with Sample Retrieval Capability:** augment helicopter with robotic arm and mobility to collect sealed samples deposited by Perseverance Rover
- **Mars Exploration:** rotorcraft to host ~2–4 kg payloads and fly 1–10 km per sortie for a total system mass of ~30 kg
- **Titan Exploration:** balloon with rotorcraft daughter ship for surface science
- Autonomy for navigation and safe landing with obstacle avoidance in rough and steep terrain



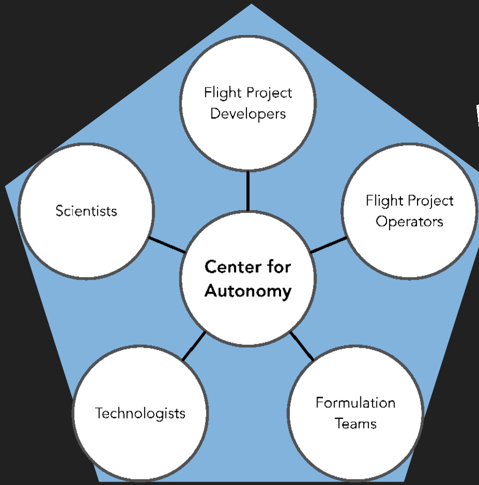
Mars 2020 Onboard Scheduler

- M2020 Rover mission is developing an onboard scheduler to use remaining resources (time, energy, data volume) from prior onboard execution.
- The Mars 2020 Onboard Scheduler is a (Rabideau and Benowitz 2017)
  - Single-shot, non-backtracking scheduler that
  - schedules in *priority first order* and
  - never removes or moves an activity after it is placed during a single scheduler run.
  - activities are not preempted
  - it does not search except for
    - valid intervals calculations
    - sleep and preheat scheduling.

AUTONOMY CENTERS

JPL's Center for Autonomous Robotics Systems (CARS)

- Coordinates, plans, and strategizes:
    - Needs
    - Approach (cross-discipline)
    - Architecture
    - Simulation
- Grows community of practice
    - Seminars (internal and external)
    - Stakeholders and practitioners
- Evolves system development processes and technologies to support flight-project needs
- Establishes strategic



Flight Project Developers

Scientists

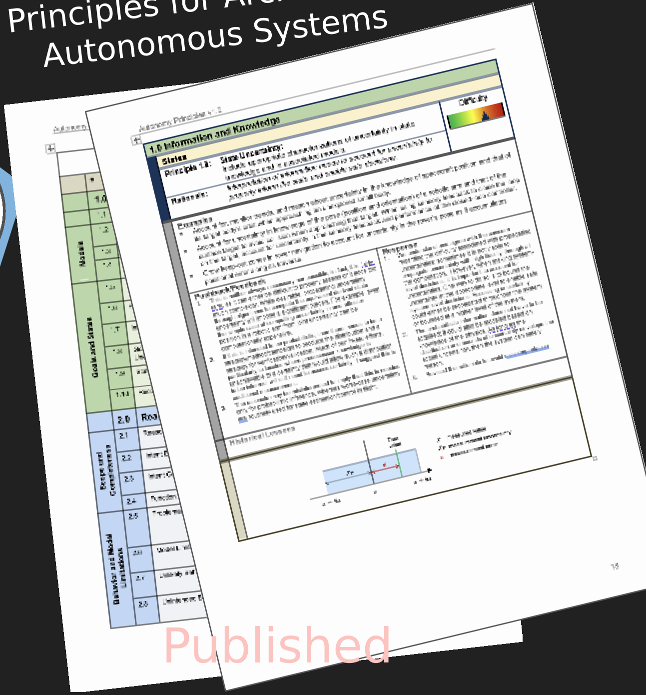
Flight Project Operators

Center for Autonomy

Technologists

Formulation Teams

Principles for Architecting Autonomous Systems



Published

Nesnas, I. A., Rasmussen, R., & Day, J. (2022). Principles for Architecting Autonomous Systems. AAS

Caltech's Center for Autonomous Systems and Technologies (CAST)

Conducts research toward these moonshots

- **Explorers:** terrestrial and space operating in harsh environments
- **Guardians:** monitoring and responding (earthquakes, tsunami)
- **Transformers:** swarm robot collaboration to enable new functions
- **Transporters:** terrestrial and space
- **Partners:** robotic helpers and

https://cast.caltech.edu/

Explorers: wind tunnel testing

Transporters: flying ambulanc

Concluding Thoughts

- Some of the most intriguing sites are currently inaccessible to state-of-the-art mobility platforms
- Mobility solutions are driven by the environment, access, payload, thermal, and energy considerations and mission requirements
- Physical contact with planetary surfaces is quite challenging
- Greater access requires innovative solutions
- Autonomy will play a critical role given the challenging interaction of a robotic platforms with the terrain
- Computing will involve reasoning, executing, assessing health, coordinating control and providing guarantees

Acknowledgements

Mobility and Lunar Environment

Mark Robinson
David Blewett
David Carrier
Fred Calef
Catherine Elder
John Elliott
Brett Kennedy
Prasun Mahanti
Mark Maimone
Patrick McGarey
Scott Moreland
Rudra Mukherjee
Raul Polit Casillas
Emerson Speyerer
Chris Voorhees
Robert Wagner
David Wettergreen
Brian Wilcox
Scott Howe
Larry Matthies
Hari Das Nayar
Will Reid

System/function Autonomy

Steve Chien
Lorraine Fesq
Andrew Johnson
Tara Estlin
Dan Gaines
Rebecca Castano

Extreme-terrain Mobility and Rover Navigation

Michael Paton
Michael McHenry
Olivier Toupet
Mark Maimone
Travis Brown
Jacek Sawoniewicz
Patrick McGarey
Jaret Matthews
Jack Morrison
Joel Burdick
Pablo Abad-Manterola
Jeffrey Edlund
Melissa Tanner
Larry Matthies
Hiro Ono
Enrico Ferrentino
Joseph Rossino
Summer students

Software and Autonomy

Mihail Pivtoraiko
Lorenzo Flueckiger
Clay Kunz
Anne Wright
Randy Sargent
Hans Utz
Chris Urmson
Ian Baldwin
Michael Fleder
Won Soo Kim
Max Bajracharya
Reid Simmons
Anne Wright
Kyohei Otsu
Venkat Rajagopalan
Luca Randazzo
Rob Reid
Khaled Ali
Kelly Breed
Martin Feather
Lorraine Fesq

BACKUP SLIDES

When Do We Need Autonomy?

Need to respond before next comm

Changes in environment or S/C

Changes are not predictable

Need Autonomy

Needs are driven by the spacecraft, environment, and goals

Example: Autonomous Approach and Measure

Challenges in deploying to M2020

- How to embed scheduler in execution
  - When to reschedule? How frequently?
  - Above impact on mission productivity?

- Because onboard scheduler is so limited, how to optimize onboard scheduler for specific sol (of multi-sol) plan?

- Challenges in wake-sleep scheduling
  (Sorry! Not enough Time!)

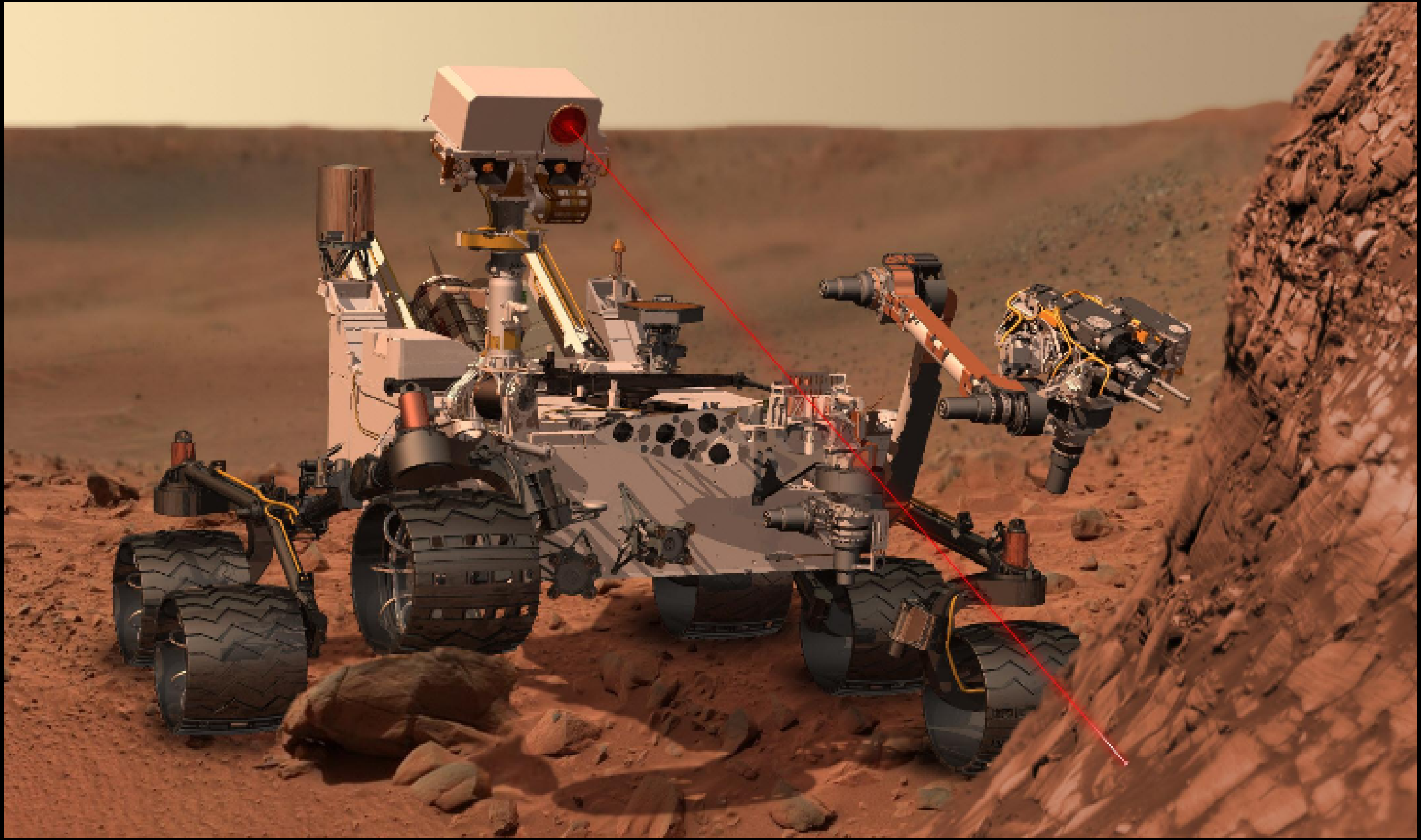
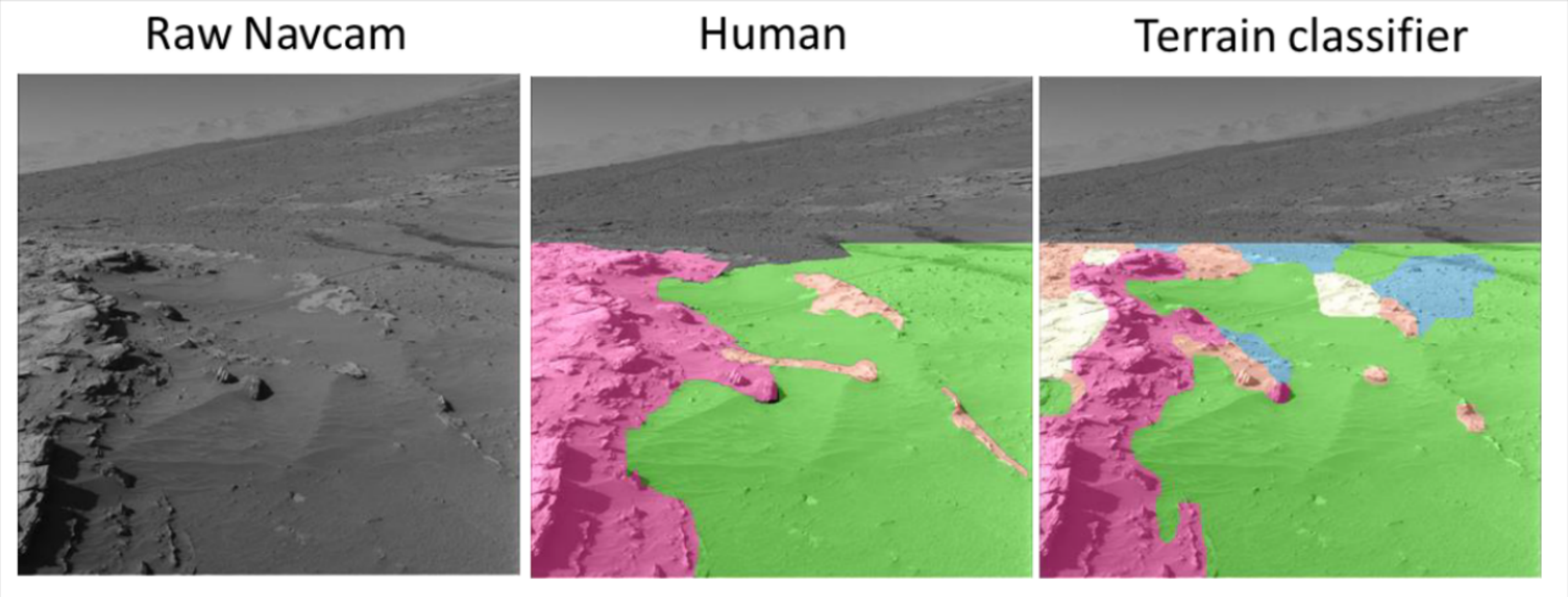


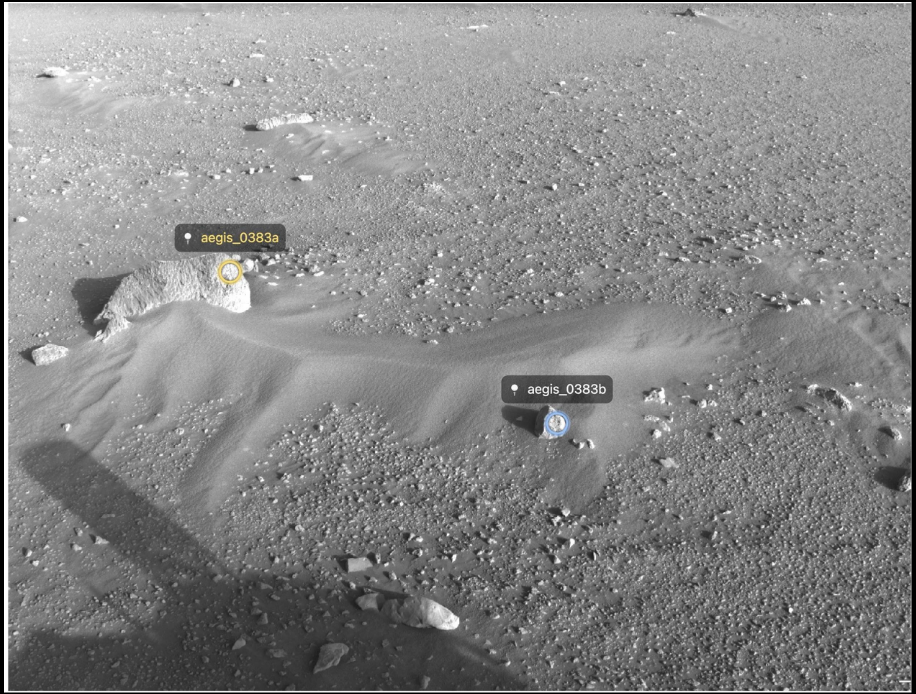
Image-based Terrain Classification

Surface Navigation



Credit: Hiro Ono

Targets Selected in First M2020 Run



SCAM and high-res Navcam data acquired on above two identified rock targets (Sol 383)

Sol 383 =
March 19, 2022

- Mars has atmosphere ~1% density of Earth’s
- Mars gravity ~1/3 Earth’s
- 1.2m / 3.9ft tip-to-tip diameter
- 1.8kg / 4lbs
- 2500RPM

MOON DIVER

Exploring a Pit’s Exposed Strata to Understand Lunar Volcanism

Presenter:	Issa A.D. Nesnas, JPL / Axel System Lead
Principal Investigator:	Laura Kerber, JPL

Jet Propulsion Laboratory
Glenn Sellar
Tibor Balint
Aaron Parness
Richard Kornfeld
Miles Smith
Patrick McGarey
Travis Brown
Eric Sunada
Kurt Gonter
Benjamin Hockman
Andrew Johnson
Yang Cheng
Aaron Curtis
Michael Paton
Kristopher Sherrill

John Hopkins/Applied Physics Laboratory
Brett Denevi

Arizona State University
Robert Wagner

University of Colorado, Boulder
Paul Hayne
Tyler Horvath

Lockheed Martin Space
Joshua B Hopkins

Honeybee Robotics
Kris Zacny

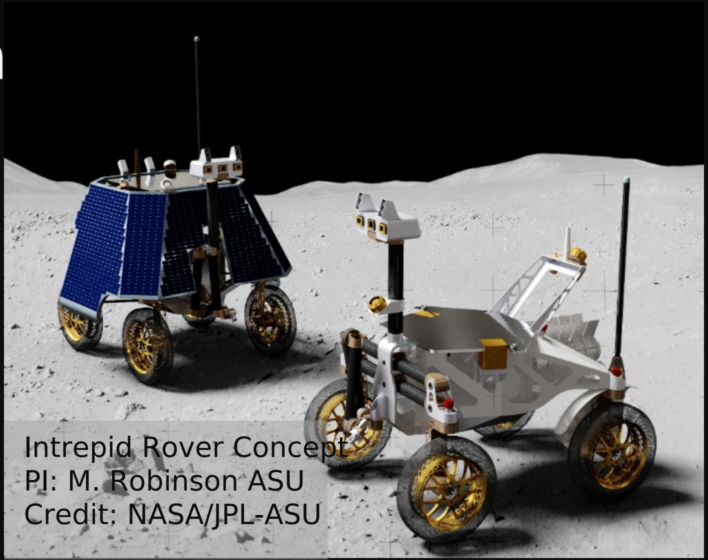
And the entire Moon Diver team
US Geological Survey
JAXA/ISAS
Brown University

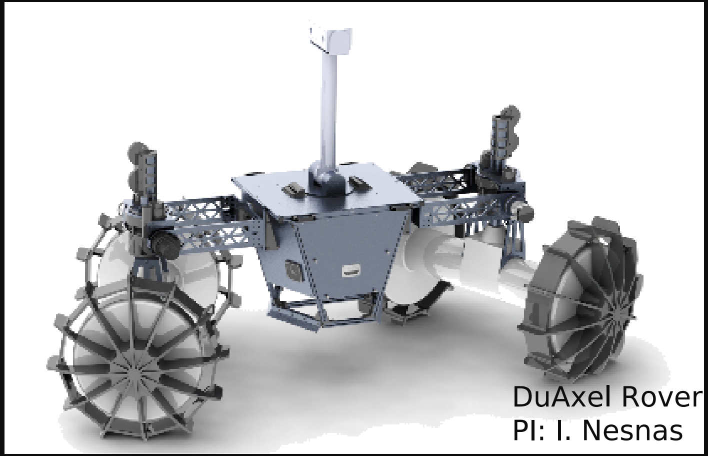
and the Moon Diver team

September 18, 2022 – International Astronautical Congress IAC-22 D1 1 x73136 CL#22-4534

Surface Mobility Consideration

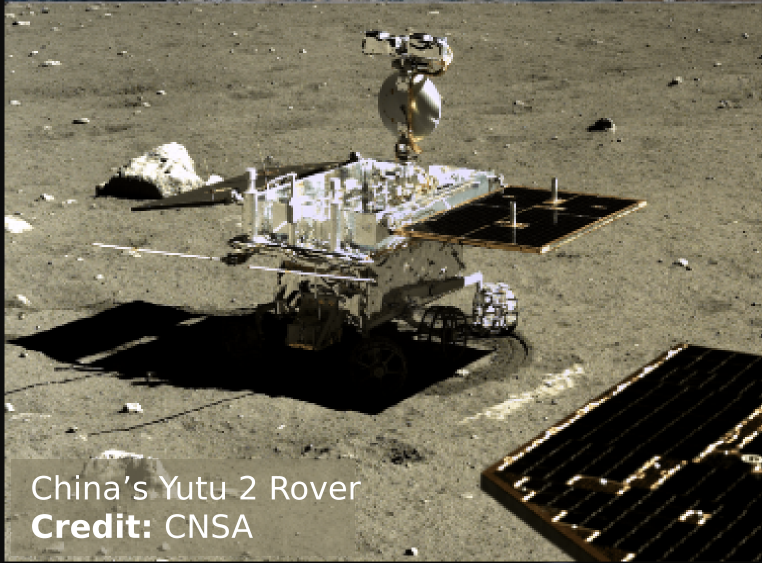
- Mobility
  - Distance
  - Speed (mechanical and operational)
  - Up/down slope (fine, compacted regolith)
  - Rock traversal
  - Ground clearance
  - Cost (J/kg/m)
- Robustness
  - Slope stability
  - Redundancy and resilience
  - Complexity
- Navigation
  - Sensing needs (dark, cryogenic)
  - Hazard distribution
  - Autonomy needs
  - Operational complexity

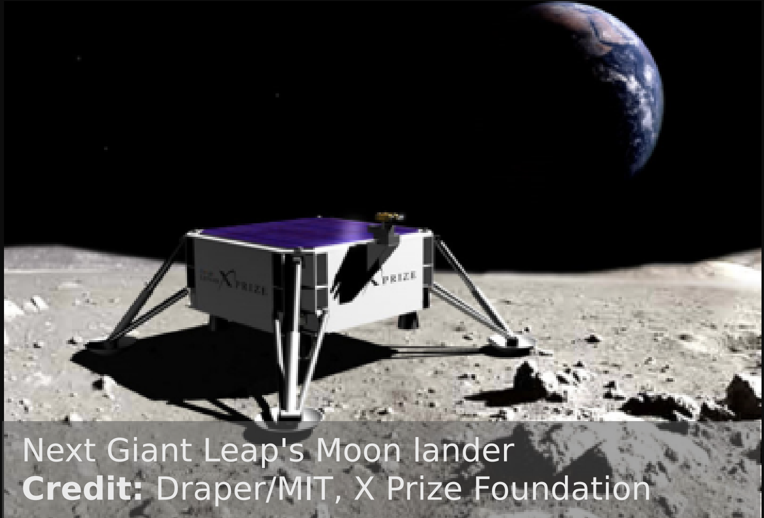

Intrepid Rover Concept
PI: M. Robinson ASU
Credit: NASA/JPL-ASU


DuAxel Rover
PI: I. Nesnas

Access Architectures

- **Surface** access (requires understanding of terrain: topography, terra-mechanics, and associated mobility hazards)
- **Above-surface** access (terrain-agnostic for large-scale mobility (ballistic hop, hovering hop, bouncing hop), but may still require regional mobility for surveys)
- **Hybrid** access (likely has larger mass and higher complexity)


China’s Yutu 2 Rover
Credit: CNSA



Next Giant Leap's Moon lander
Credit: Draper/MIT, X Prize Foundation

Mobility Design Trades

Steering configuration

- Skid
- Ackerman (partially steerable)
- Omni (fully steerable)

Suspension

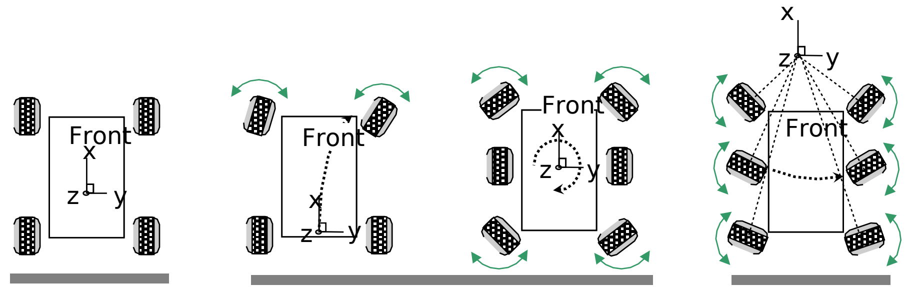
- Active
- Passive

Wheels

- Shape/size
- Number (2, 3, 4, 6, etc.)
- Design (rigid, compliant, grouser size, elliptic, hubless, etc.)

For energy design:
Use average trafficability
For mobility design
Use edge cases (for non-human operated)

Lunar Sourcebook - Table 9.14, p. 529



(1) Skid (no steering)

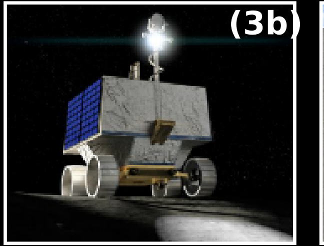
(2) Ackerman (partially steerable)

(3) Omni (fully-steerable)

(a) Active suspension (actuated links)

(b) Passive suspension (complies to terrain)

(2a)

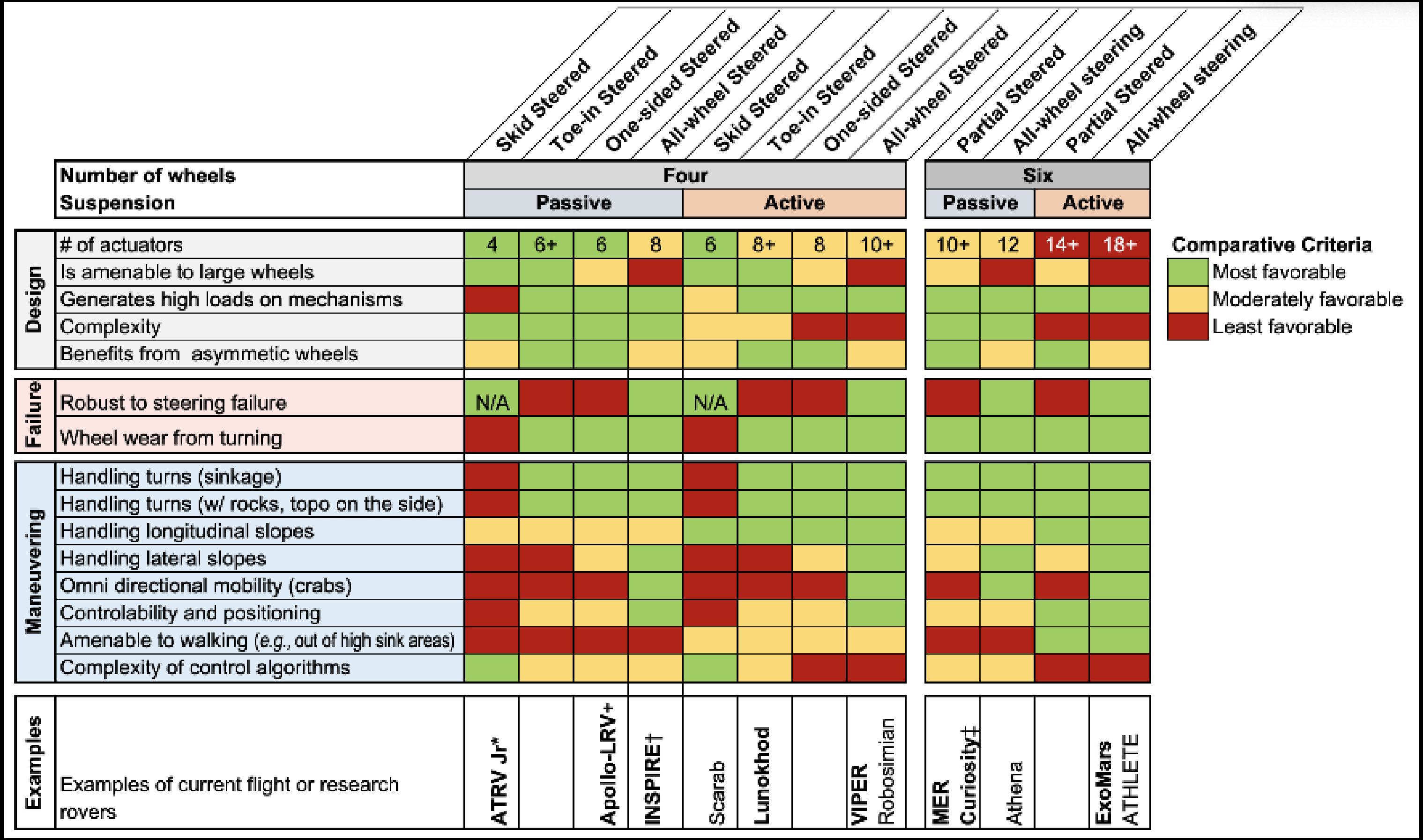


(3b)

(1b)

(3b)

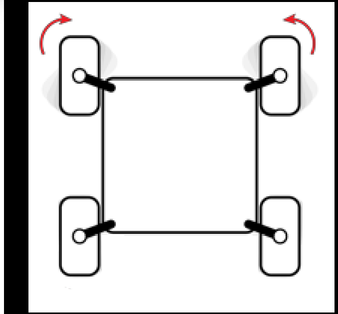
Mobility Design Trades



	Number of wheels	Four								Six			
	Suspension	Passive				Active				Passive		Active	
		Skid Steered	Toe-in Steered	One-sided Steered	All-wheel Steered	Skid Steered	Toe-in Steered	One-sided Steered	All-wheel Steered	Partial Steered	All-wheel steering	Partial Steered	All-wheel steering
Design	# of actuators	🟩 4	🟩 6+	🟩 6	🟨 8	🟩 6	🟨 8+	🟨 8	🟨 10+	🟨 10+	🟨 12	🟥 14+	🟥 18+
	Is amenable to large wheels	🟩	🟩	🟨	🟥	🟩	🟩	🟨	🟥	🟨	🟥	🟨	🟥
	Generates high loads on mechanisms	🟥	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Complexity	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟥	🟩	🟩	🟥	🟥
	Benefits from asymmetic wheels	🟨	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟩	🟨	🟩	🟨
Failure	Robust to steering failure	🟩 N/A	🟥	🟥	🟩	🟩 N/A	🟥	🟥	🟩	🟥	🟩	🟥	🟩
	Wheel wear from turning	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Maneuvering	Handling turns (sinkage)	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Handling turns (w/ rocks, topo on the side)	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Handling longitudinal slopes	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩
	Handling lateral slopes	🟥	🟥	🟨	🟩	🟥	🟥	🟨	🟩	🟨	🟩	🟨	🟩
	Omni directional mobility (crabs)	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟩
	Controlability and positioning	🟥	🟨	🟨	🟩	🟥	🟨	🟨	🟩	🟨	🟨	🟩	🟩
	Amenable to walking (*e.g.*, out of high sink areas)	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟥	🟥	🟩	🟩
	Complexity of control algorithms	🟩	🟨	🟨	🟨	🟩	🟨	🟥	🟥	🟨	🟨	🟥	🟥
Examples	Examples of current flight or research rovers	ATRV Jr*		Apollo-LRV+	INSPIRE†	Scarab	Lunokhod		VIPER Robosimian	MER Curiosity‡	Athena		ExoMars ATHLETE

Comparative Criteria

- 🟩 Most favorable
- 🟨 Moderately favorable
- 🟥 Least favorable

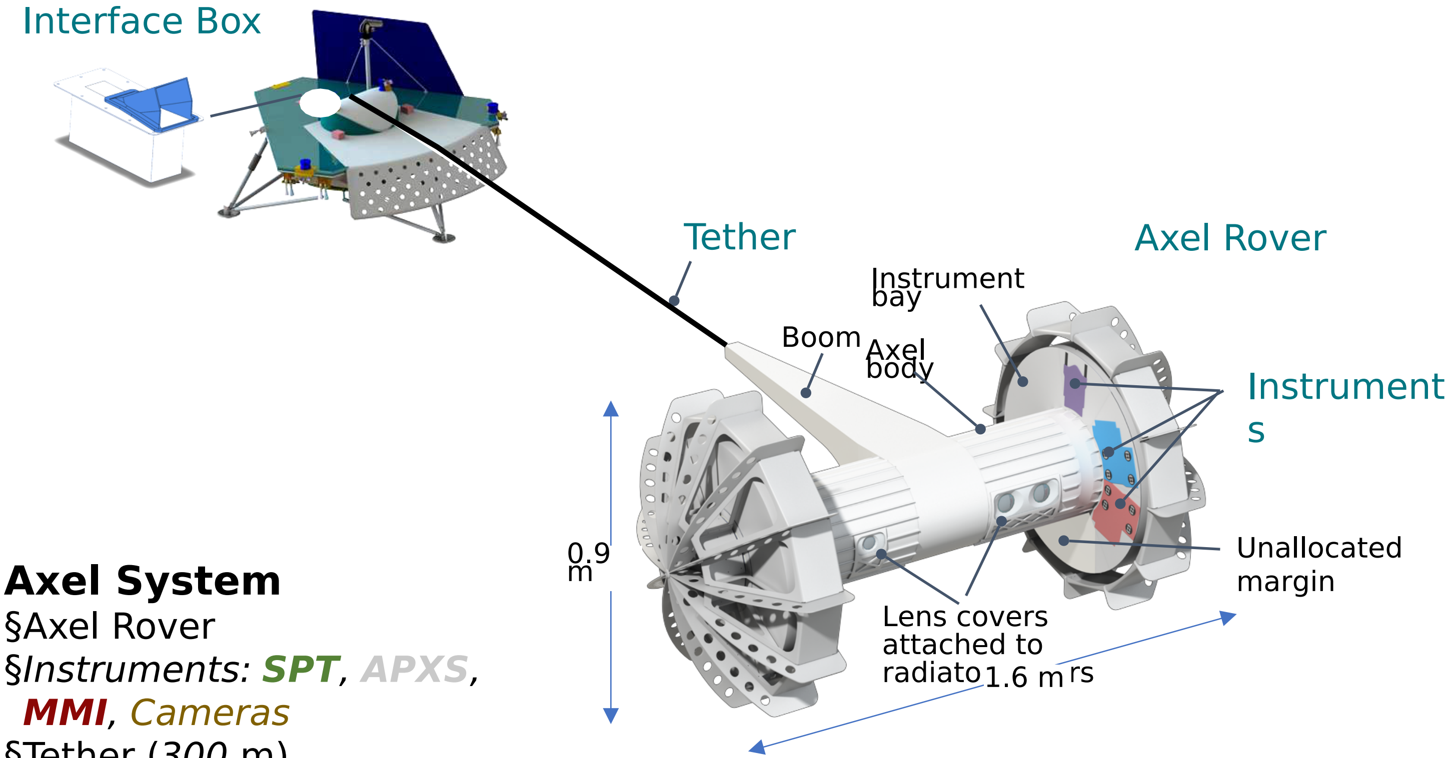


Toe-in steered

Asymmetric wheeled vehicle

Qualitative assessment https://science.nasa.gov/science-pink/s3fs-public/atoms/files/Lunar%20INTREPID.pdf

The Flight System



Axel System

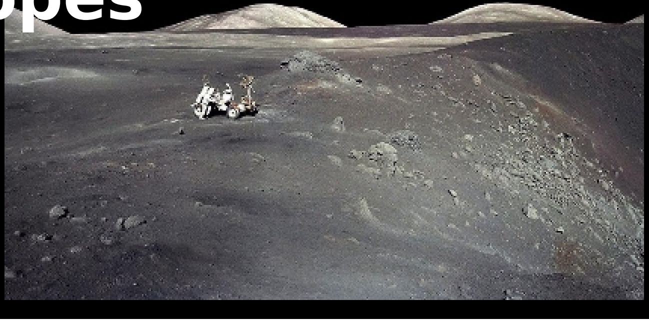
§Axel Rover

§*Instruments:* ***SPT***, ***APXS***, ***MMI***, *Cameras*

§Tether (*300* m)

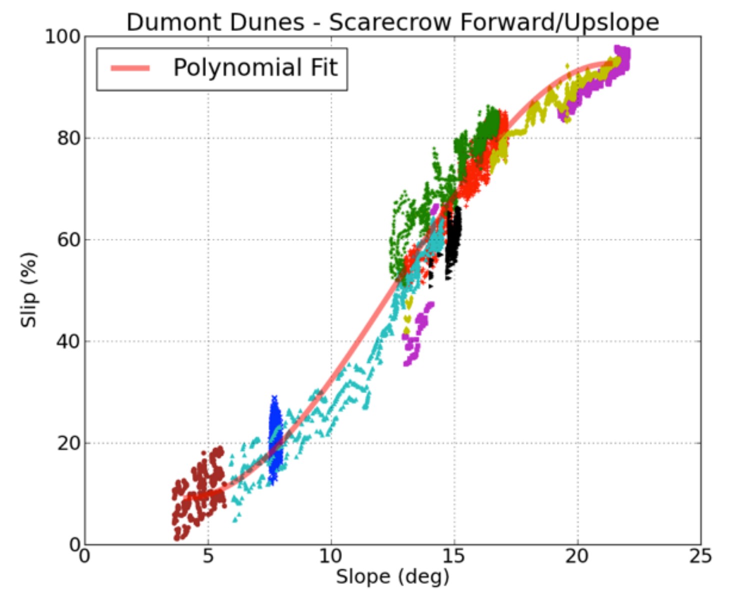
§Interface Box

Key Challenge: Soft Regolith Slopes



Varies based on regolith terra-mechanical properties, which would depend on grain size, compaction, and cohesion due to hydroxyl content

- Based on Apollo, mobility in simulants up to 15° – 20°
- From Mars mobility experiments, slip in soft regolith could reach:
  - 60% at 15°and
  - 100% at 25°



Heverly, M., Matthews, J., Lin, J., Fuller, D., Maimone, M., Biesiadecki, J., & Leichty, J. (2013). Traverse performance characterization for the Mars Science Laboratory rover. *Journal of Field Robotics*, *30*(6), 835-846.

What Data Do We Have to Inform Mobility near/in PSR?

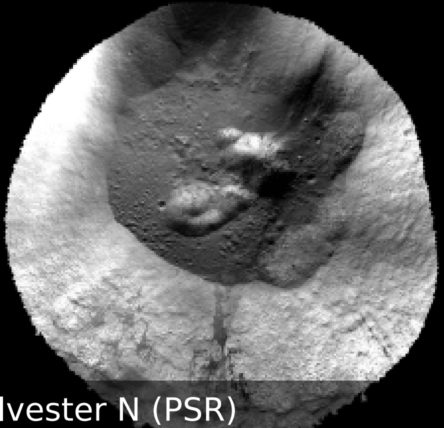
	Resolution	Coverage	Source
Spatial	**0.5 – 1.5 m/pixel**	Full spatial coverage with small/large incidence angles	LRO Narrow Angle Camera
	1 × 40 m/pixel cross × down track SNR 10–20	PSR long-exposed images from scattered light (no distinct morphology; strange photometric effect)	LRO Narrow Angle Camera
	200 m/pixel	Full thermal coverage to infer rock distribution from images	LRO Diviner Lunar Radiometer
3D	**60 m × 60 m** (	Nearly full Digital	Kaguya
	2 – 5 m/pixel	Very limited coverage Digital Topographic Map	LRO Narrow Angle Camera

Futur

Shado

Lunar Flashlight (NASA/JPL-Caltech)

Data at the scale of surface asset is very limited.
Knowledge is inferred from analogy sites and same expected surface processes



Sylvester N (PSR)
Credit: NASA/GSFC/Arizona State U

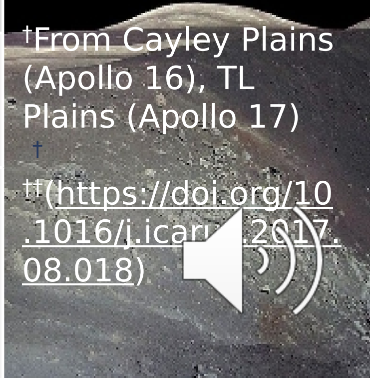
Lunar Flashlight – Launch: Nov 2020 (SLS EM-1) - Credit:

PSR Surface Mobility Key Parameters

	Description	Value	Comments
Hazard Distribution	Rock distribution	1% 10%	Between crater Around craters
	Young crater distribution	100s m apart	
Regolith	Angle of repose	32°–36°	Angle of repose is independent of gravity and based on physical properties of grains
	Compaction	Soft Soft	In interior of crater walls* Between interior walls and floors
	Cohesion	varies	Interior crater rims < intercrater areas Intercrater areas < crater rims**
Crater Walls	Large crater slopes	5° – 35°+	Several craters have global routes with < 25° (no data exists on local slope at vehicle scale).
	Small crater depths (35 – 50 m)† (< 35 m no reliable DTM data but expected to be	0.17 fresh 0.10 median 0.08 old	Slopes could exceed 20° for fresh craters. Expects < 35 m craters to have lower depth/ ratio because they have less compact walls and would degrade faster. Craters that form in solid rock (very rare

Sources:
- M. Robinson/Intrepid study
- D. Carrier
- 2006 Lunar Mobility Review David A. Kring

*Apollo 15 LRV got stuck. Lunokhod 2 encountered soft soils on inside crater walls



†From Cayley Plains (Apollo 16), TL Plains (Apollo 17)

†

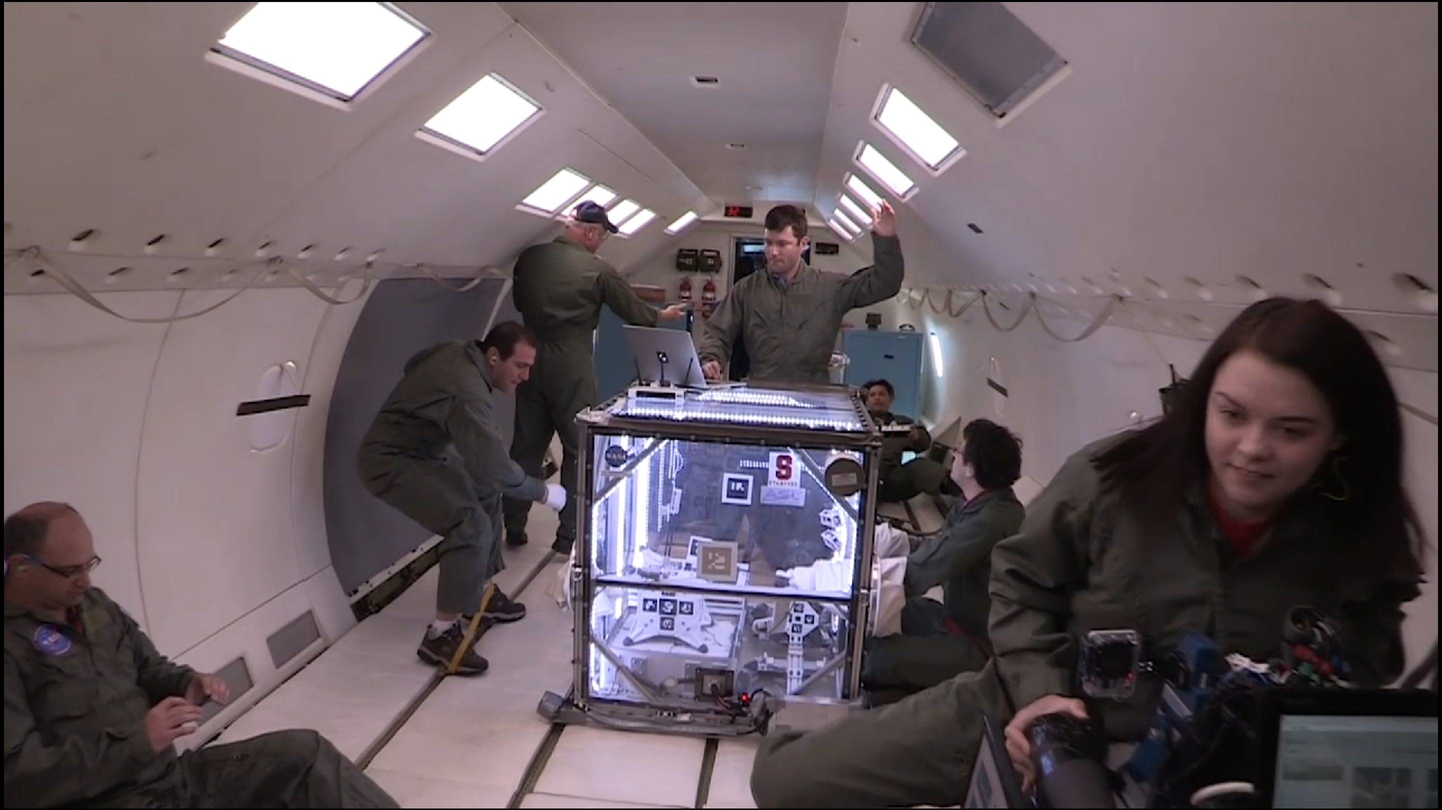
††(https://doi.org/10.1016/j.icaru[illegible].2017.08.018)

How to Explore the Surface of Comets and Asteroids

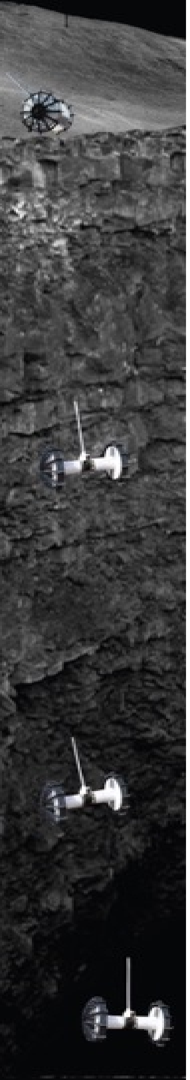
Jet Propulsion Laboratory
California Institute of Technology

HOPPING TUMBLING MOBILITY

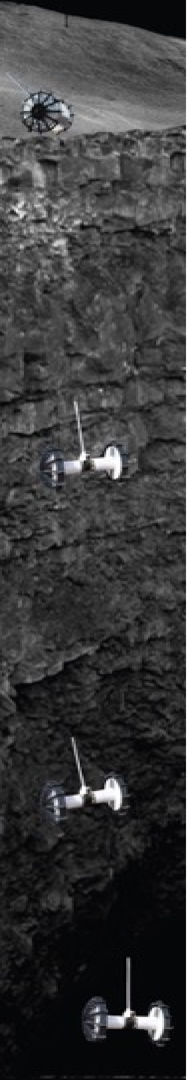
HEDGEHOG ROBOT

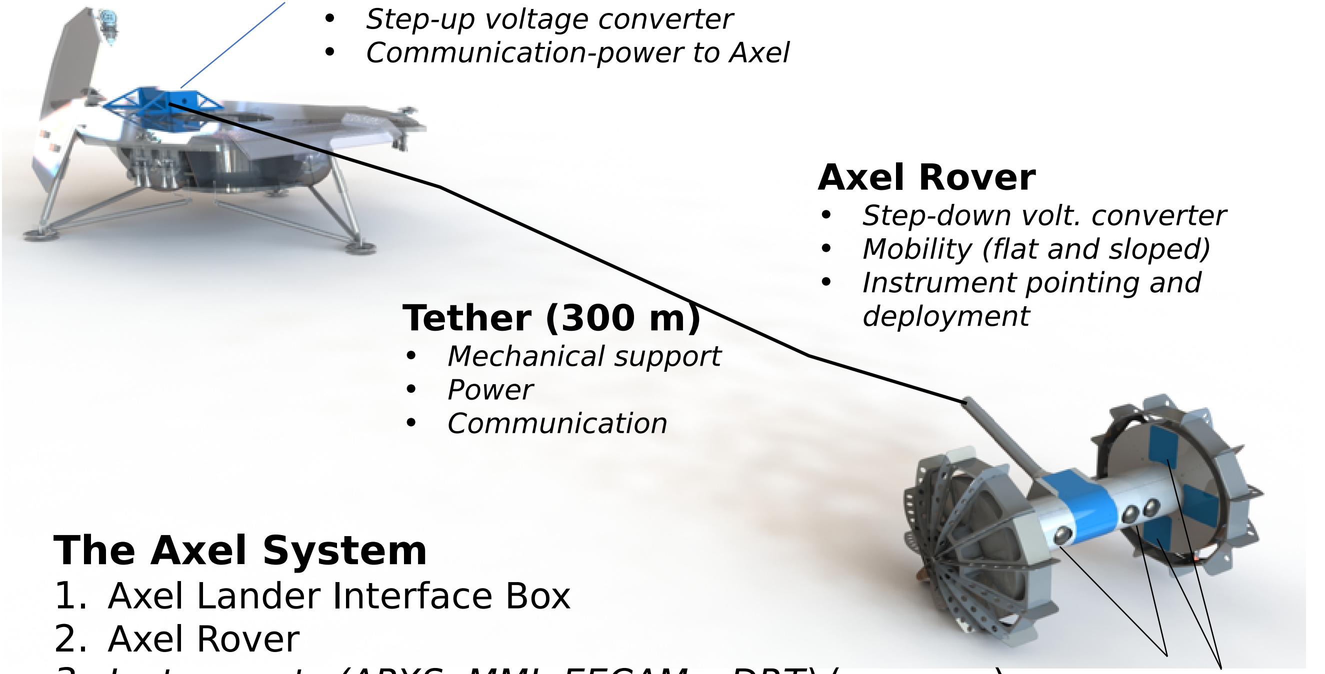


Credit: I. Nesnas, R. Reid (JPL), M. Pavone (Stanford), B. Hockman (2015)



Axel System Overview





Interface Box
- *Mechanical anchor to lander*
- *Step-up voltage converter*
- *Communication-power to Axel*

Axel Rover
- *Step-down volt. converter*
- *Mobility (flat and sloped)*
- *Instrument pointing and deployment*

Tether (300 m)
- *Mechanical support*
- *Power*
- *Communication*

The Axel System
1. Axel Lander Interface Box
2. Axel Rover
3. *Instruments (APXS, MMI, EECAMs, DRT)* (on rover)
4. Tether (on rover)

Instruments

Steep and Extreme Terrain Mobility

1994 Dante II – CMU

J. Bares, D. Wettergreen, IJRR 1999

- Tethered walking robot
- Explored Mt. Spurr
- Robot side winch

2007 SCARAB Lunar Rover

D. Wettergreen, R. Whitaker, CMU

- Demonstrated slope mobility and drilling
- Untethered wheeled rover with active suspension

2007 ATHLETE Legged Lunar Robot

B. Wilcox, et.al. "Athlete: A cargo handling and manipulation robot for the moon," JFR, 2007.

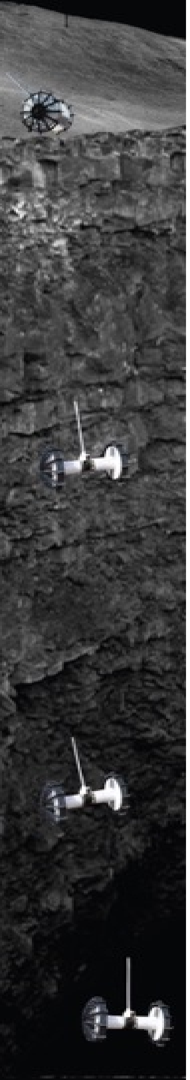
- Six-legged rover with self-anchoring and onboard tether for

2015 Robosimian Wheel-Legged Robot

(B. Kennedy)

W. Reid, et al, " Mobility Mode Evaluation of a Wheel-on-Limb Rover on Glacial Ice Analogous to Europa Terrain." 2020

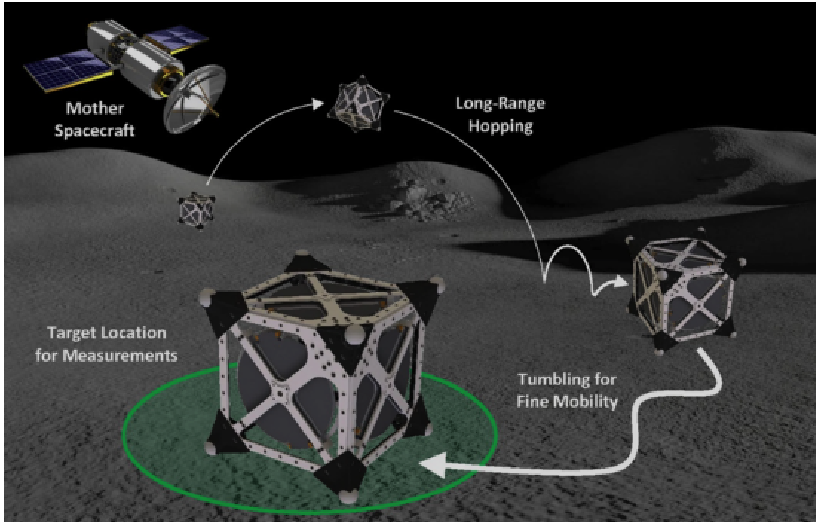
- Four-legged rover wheel-on-limb



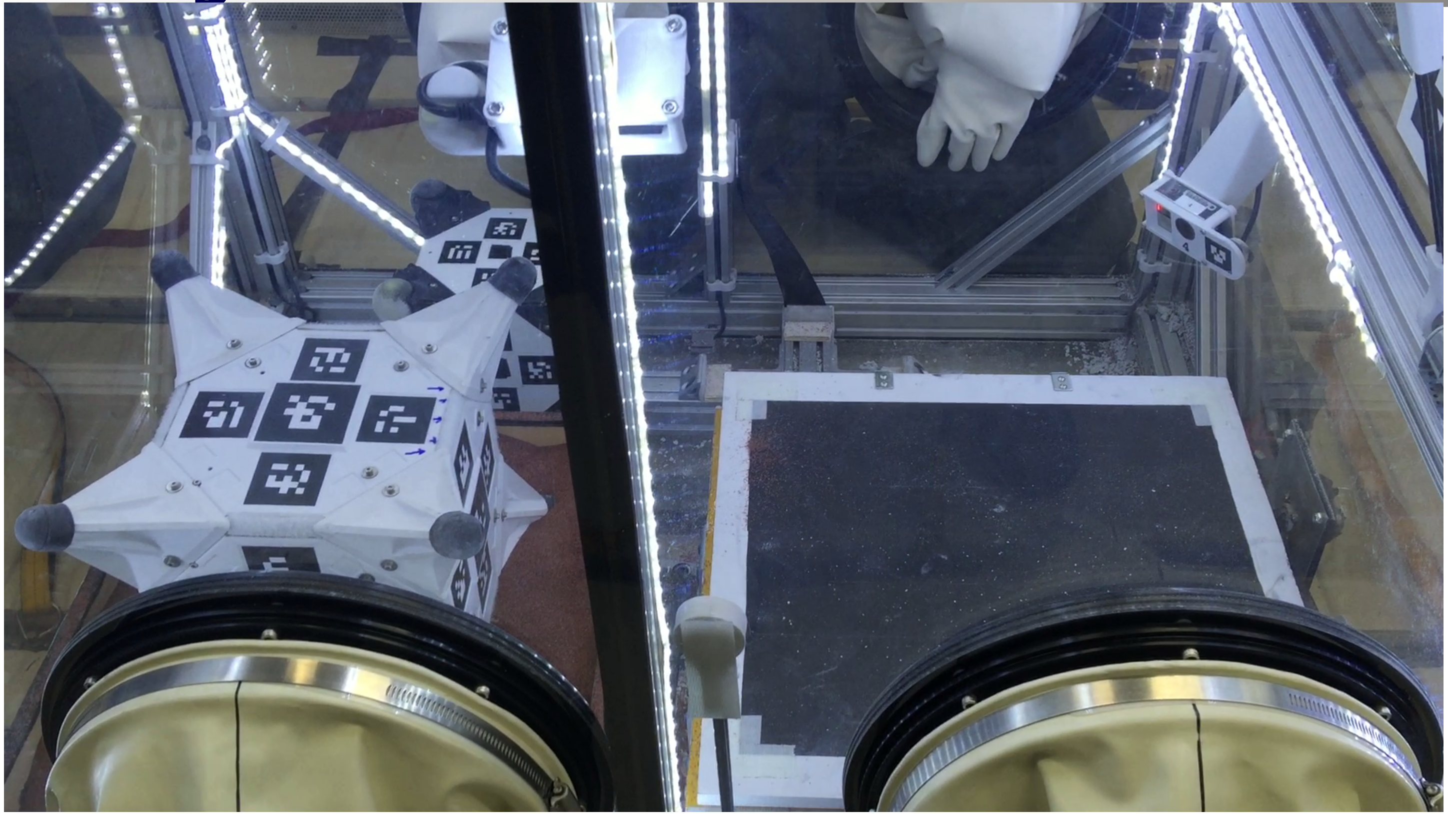
Arroyo Live Demo

Research Prototype: Hedgehog

JPL and Stanford (Pavone)



Flown on NASA’s Parabolic Flight



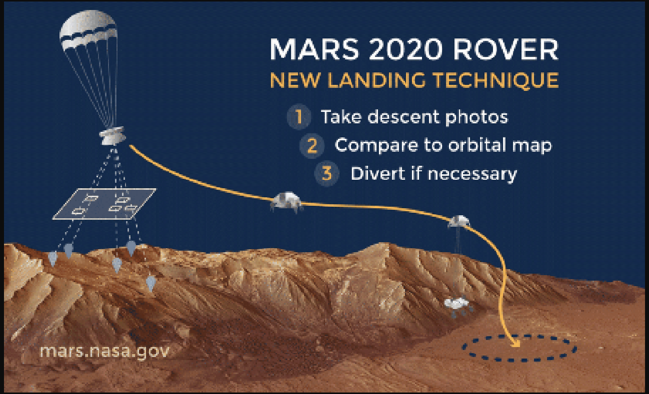
- Hedgehog prototype: 2 degree incline with 6 Nm brakes (video 8x realtime)

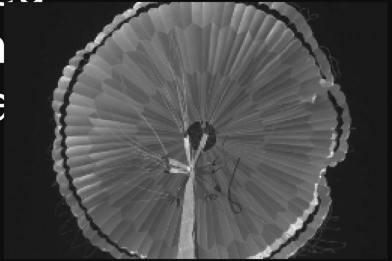
Mars Entry, Descent and Landing

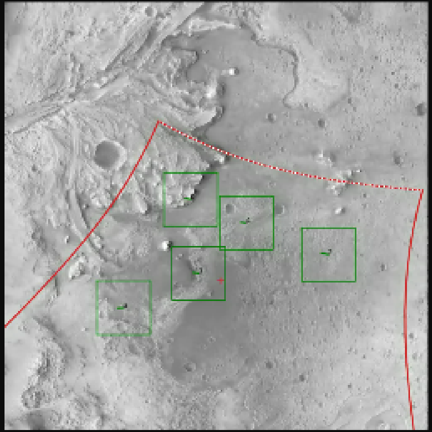
Flight Deployed

- **2003 Mars Exploration Rover:** descent imagery used to estimate and control horizontal velocity
- **2011 Mars Science Laboratory:** closed-loop guidance, navigation and control (GNC) to guide large lander to a soft touchdown
- **2020 Perseverance Mission:** closed-loop GNC with terrain-relative naviga us sa lar

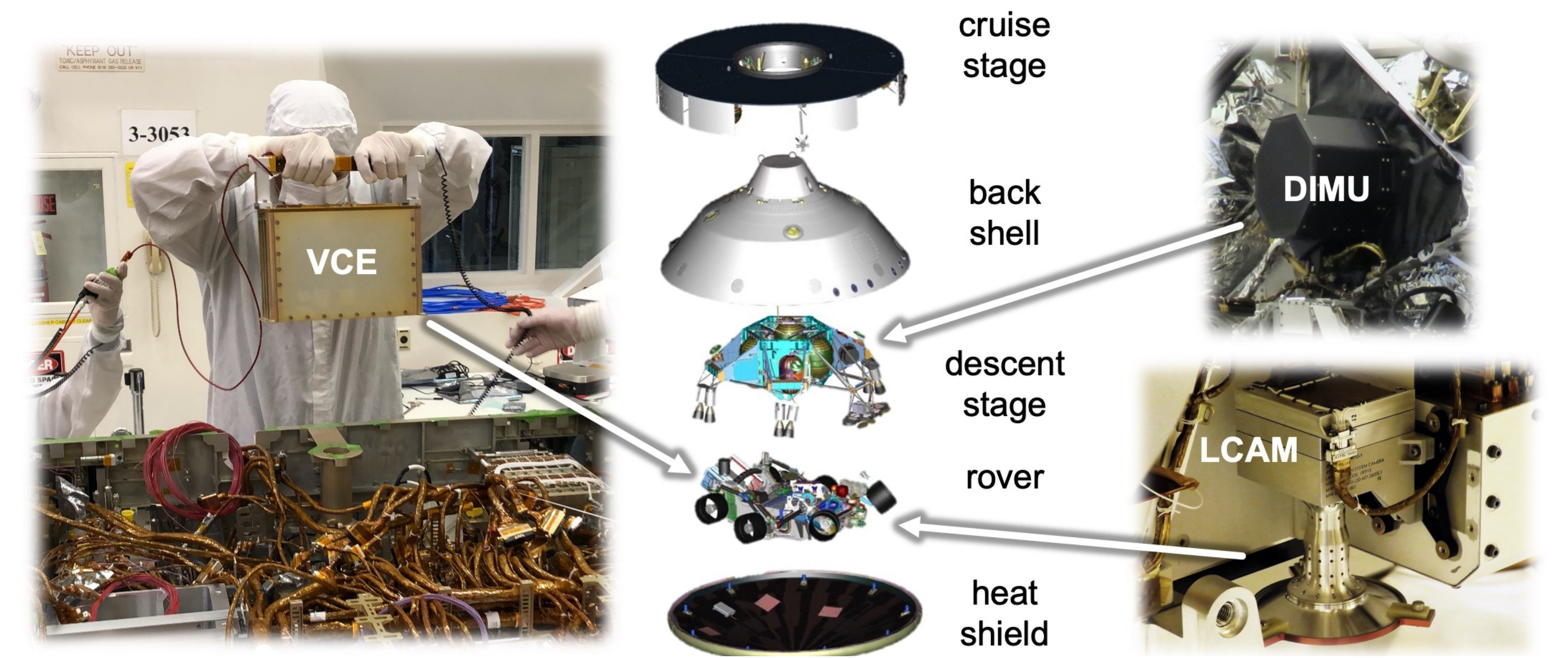
Year	Mission	Landing Ellipse
2003	Mars Exploration Rover	150 km × 20 km
2011	Mars Science Lab	20 km × 7 km
2020	Mars 2020	10 km × 10 km







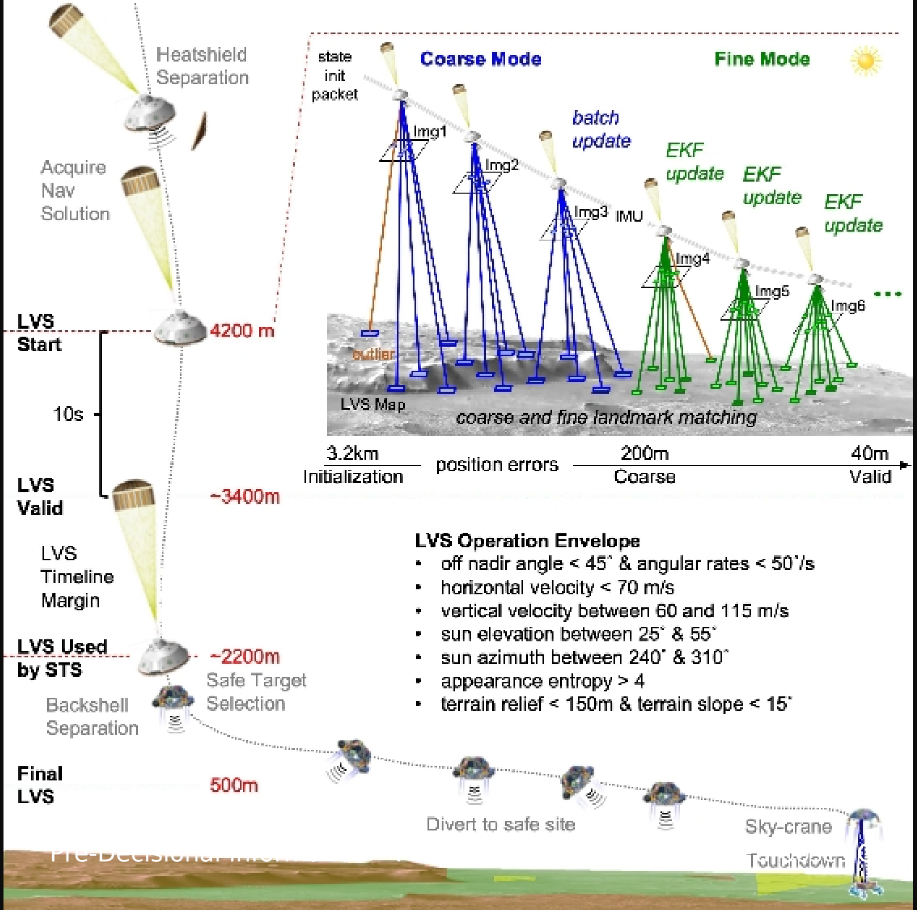
Flight System (lander vision)



VCE: Vision Compute Element **LCAM:** Lander Camera **DIMU:** Descent inertial measurement unit

Credit: Andrew Johnson

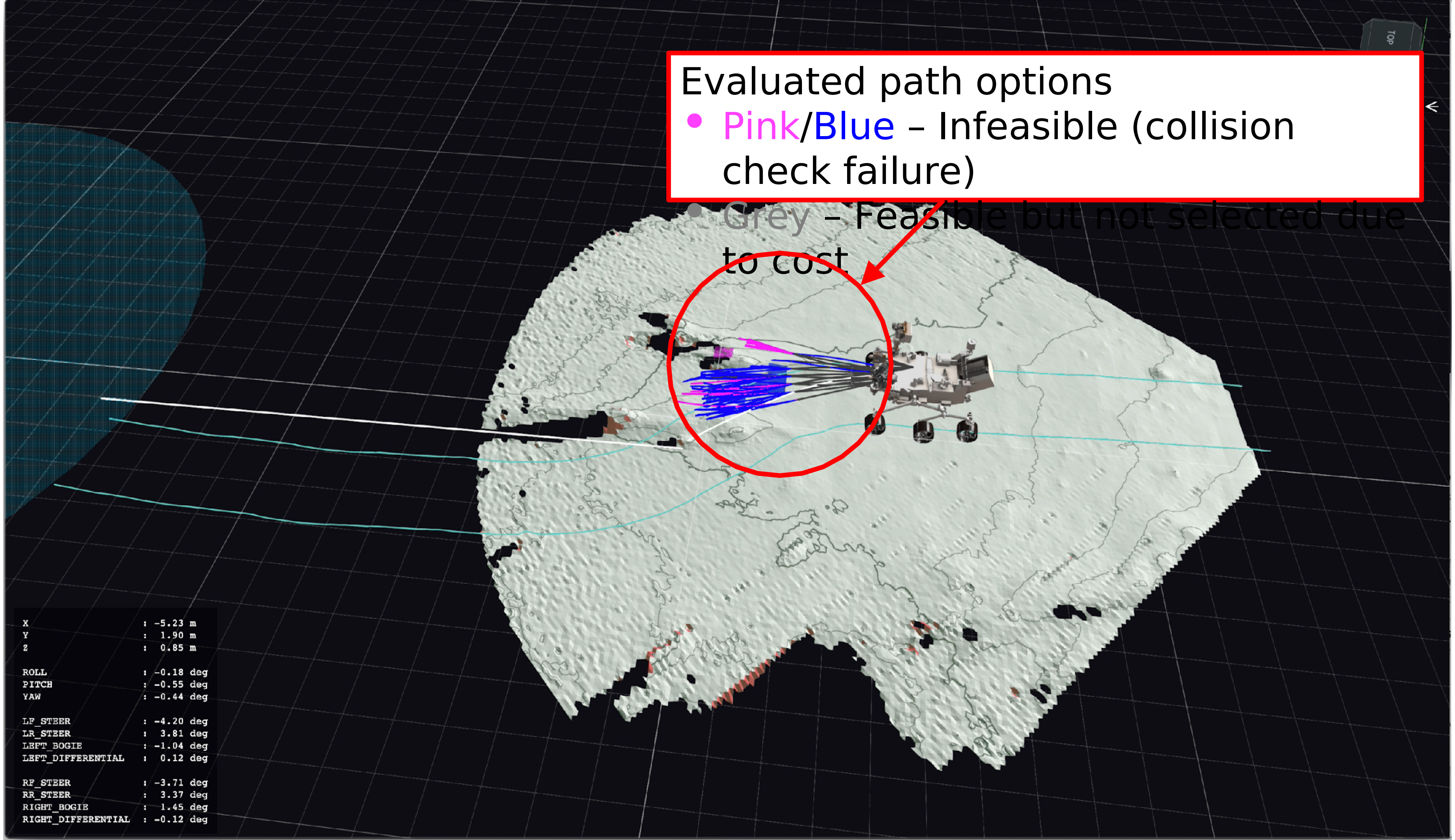
Mars 2020 Terrain Relative Navigation



LVS Operation Envelope

- off nadir angle < 45° & angular rates < 50°/s
- horizontal velocity < 70 m/s
- vertical velocity between 60 and 115 m/s
- sun elevation between 25° & 55°
- sun azimuth between 240° & 310°
- appearance entropy > 4
- terrain relief < 150m & terrain slope < 15°

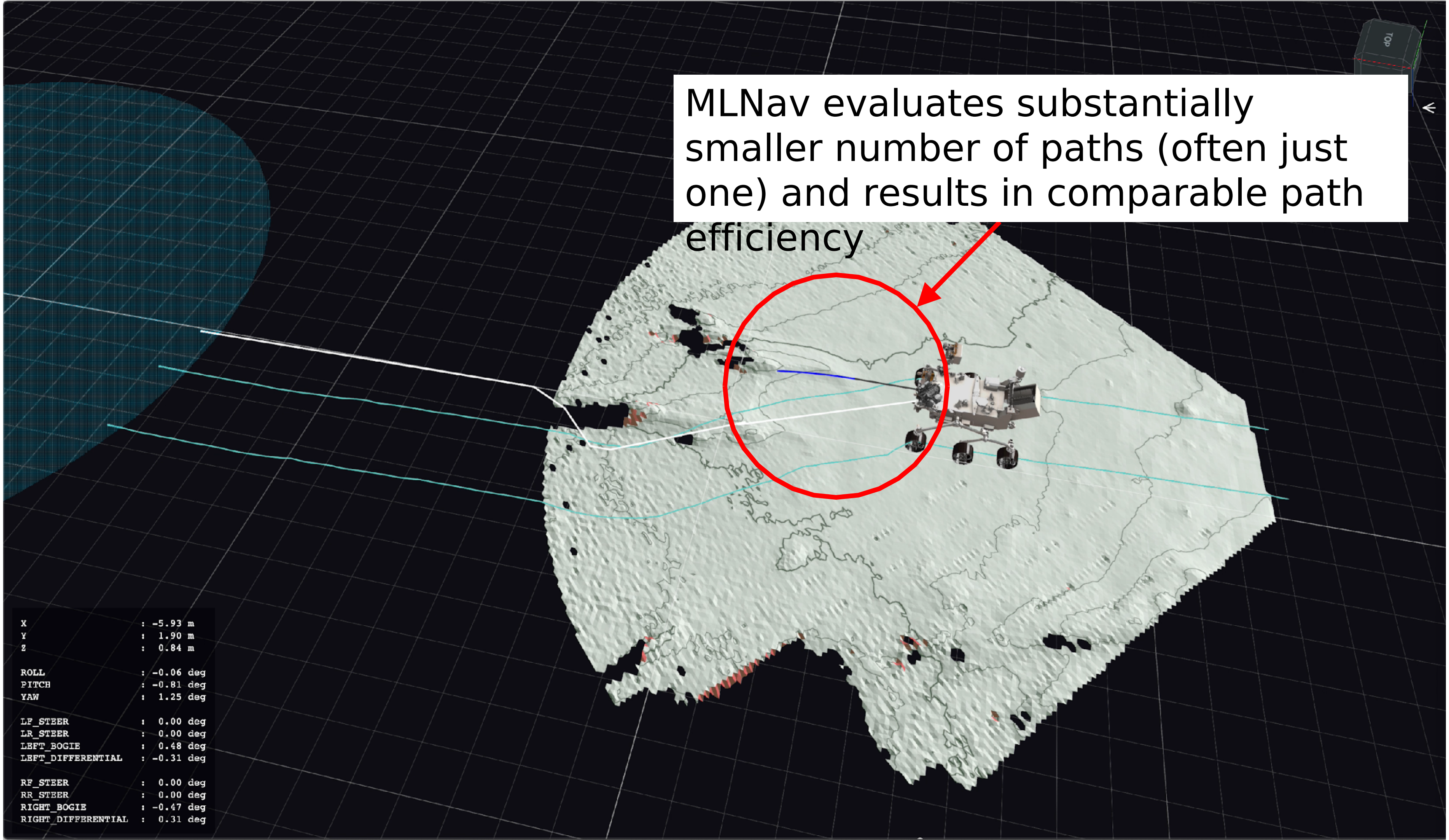
Credit: Andrew Johnson



Evaluated path options

- Pink/Blue – Infeasible (collision check failure)
- Grey – Feasible but not selected due to cost

```
X                     :  -5.23 m
Y                     :   1.90 m
Z                     :   0.85 m

ROLL                  :  -0.18 deg
PITCH                 :  -0.55 deg
YAW                   :  -0.44 deg

LF_STEER              :  -4.20 deg
LR_STEER              :   3.81 deg
LEFT_BOGIE            :  -1.04 deg
LEFT_DIFFERENTIAL     :   0.12 deg

RF_STEER              :  -3.71 deg
RR_STEER              :   3.37 deg
RIGHT_BOGIE           :   1.45 deg
RIGHT_DIFFERENTIAL    :  -0.12 deg
```

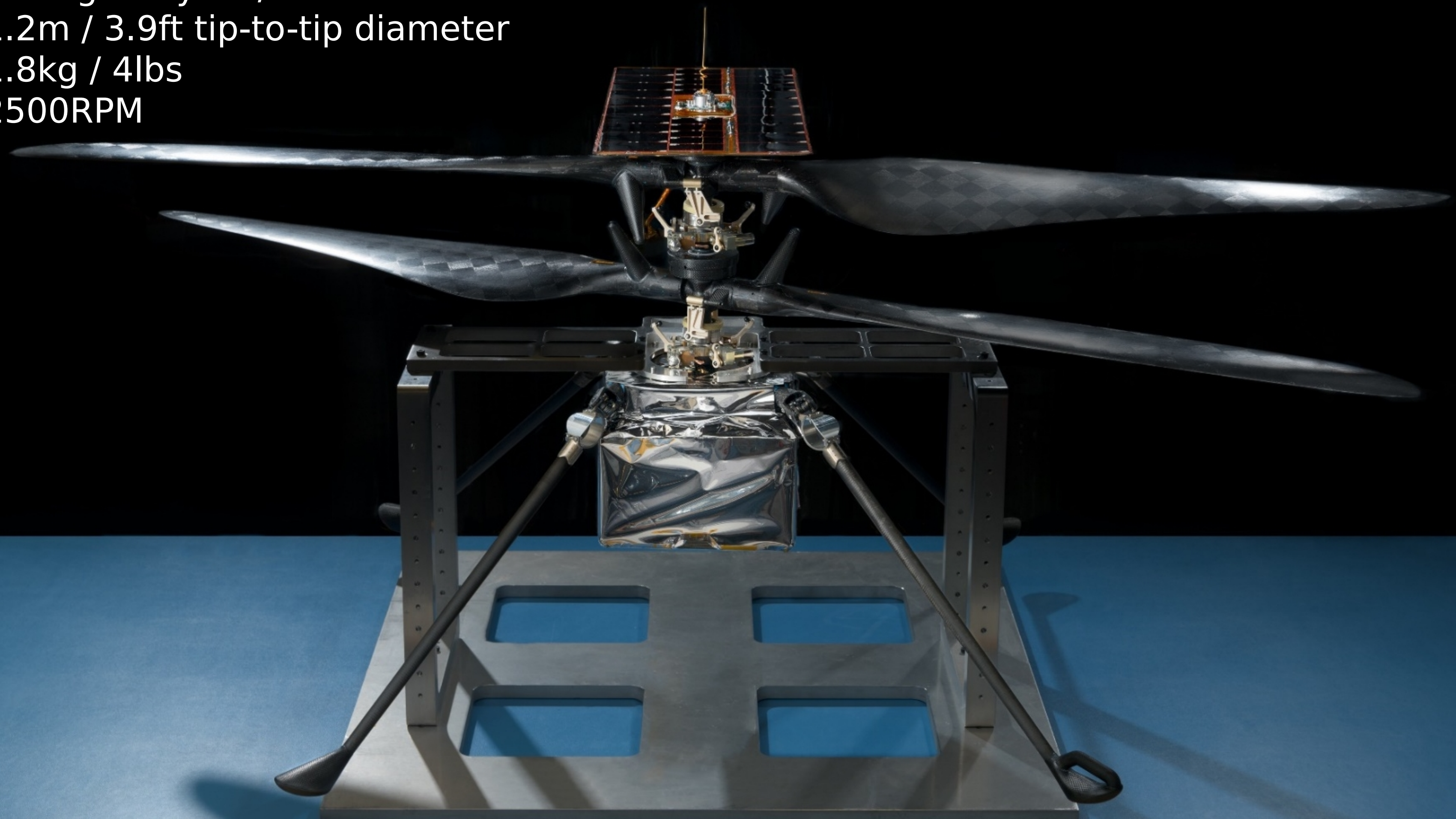


MLNav evaluates substantially smaller number of paths (often just one) and results in comparable path efficiency

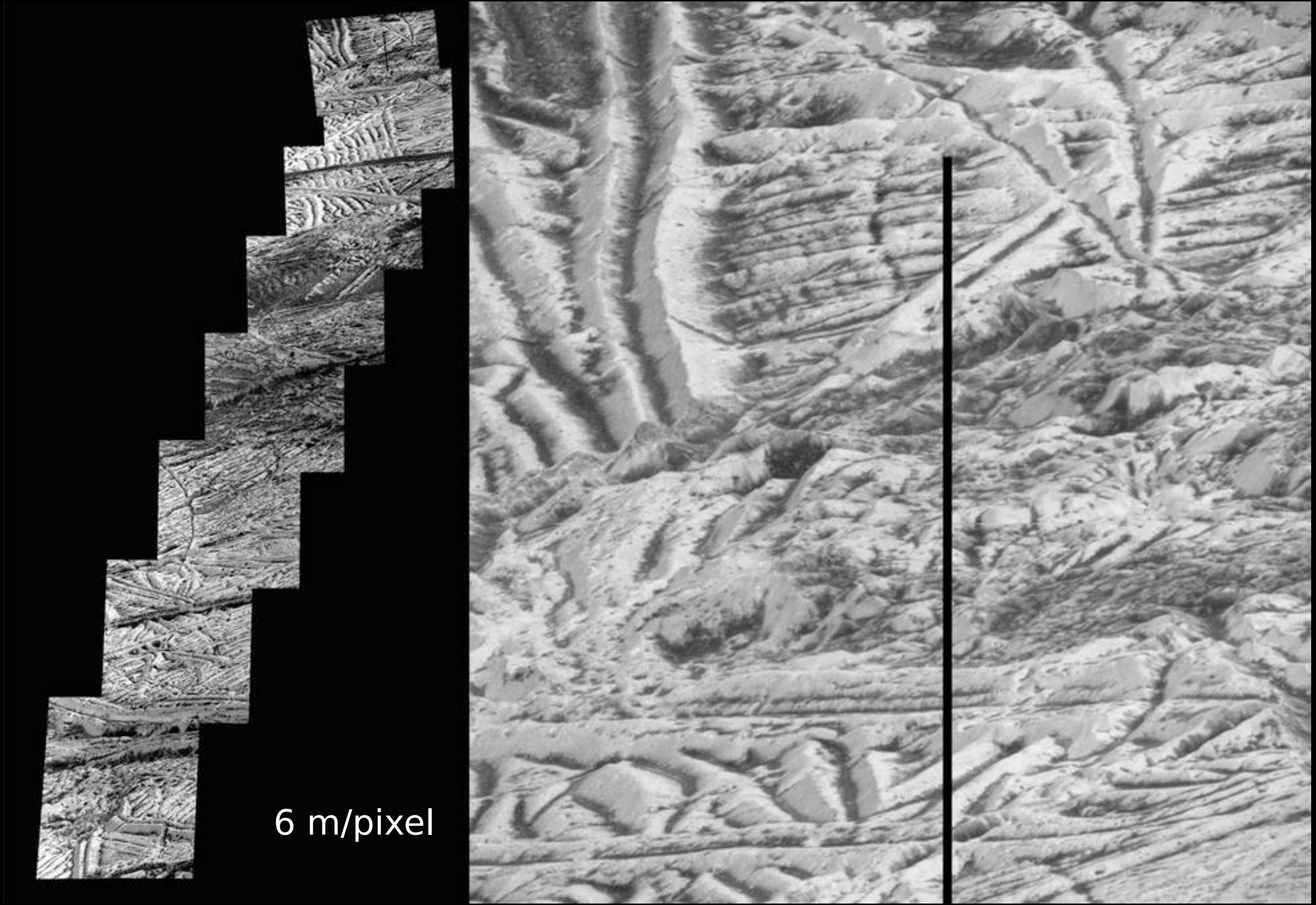
```
X                     : -5.93 m
Y                     :  1.90 m
Z                     :  0.84 m

ROLL                  : -0.06 deg
PITCH                 : -0.81 deg
YAW                   :  1.25 deg

LF_STEER              :  0.00 deg
LR_STEER              :  0.00 deg
LEFT_BOGIE            :  0.48 deg
LEFT_DIFFERENTIAL     : -0.31 deg

RF_STEER              :  0.00 deg
RR_STEER              :  0.00 deg
RIGHT_BOGIE           : -0.47 deg
RIGHT_DIFFERENTIAL    :  0.31 deg
```

The Experiments

- Mars has atmosphere ~1% density of Earth’s
- Mars gravity ~1/3 Earth’s
- 1.2m / 3.9ft tip-to-tip diameter
- 1.8kg / 4lbs
- 2500RPM



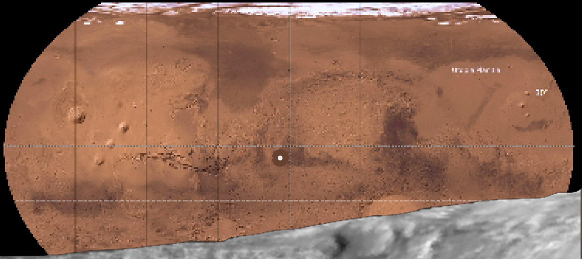
Exploring Europa’s Surface?

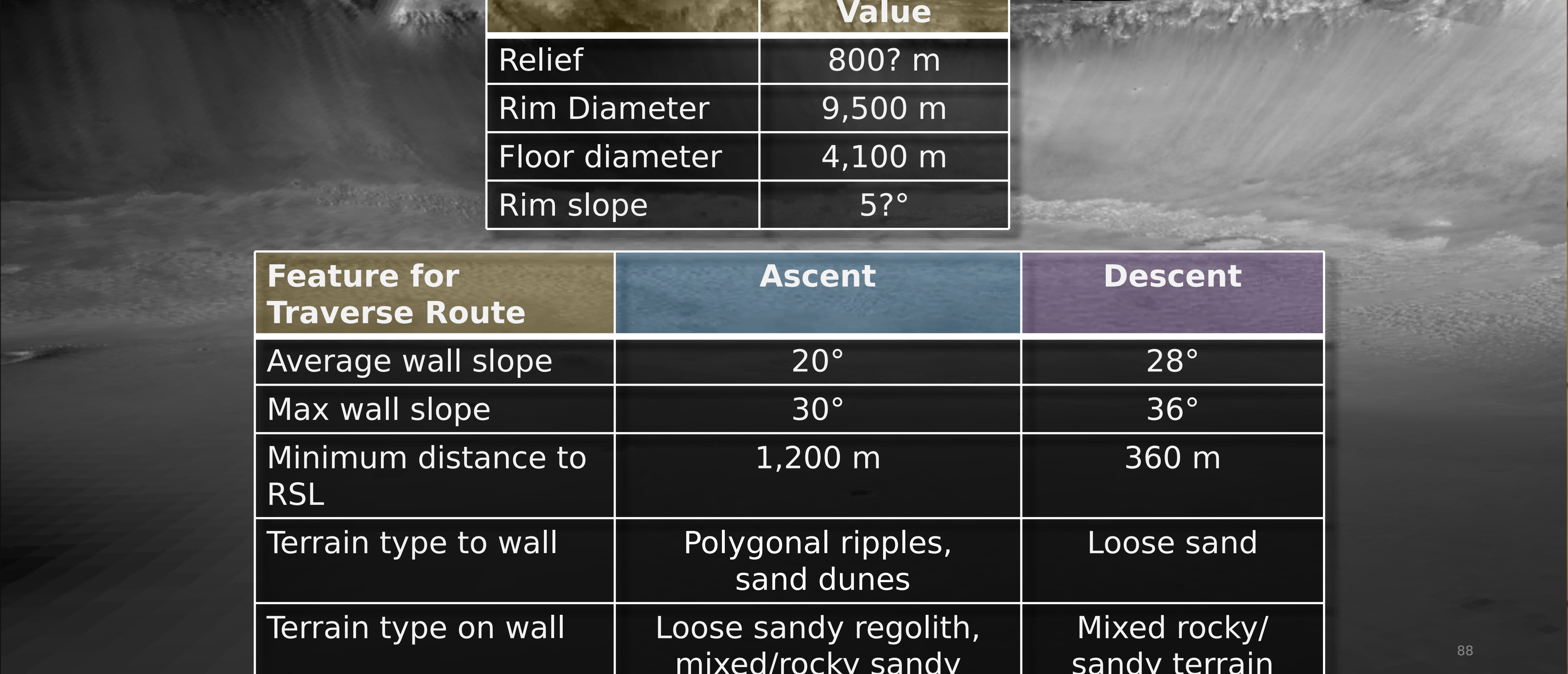


Andapa Crater

Elevation: -2,200 m Long/Lat: (-4.7, -5.3)

MMGIS

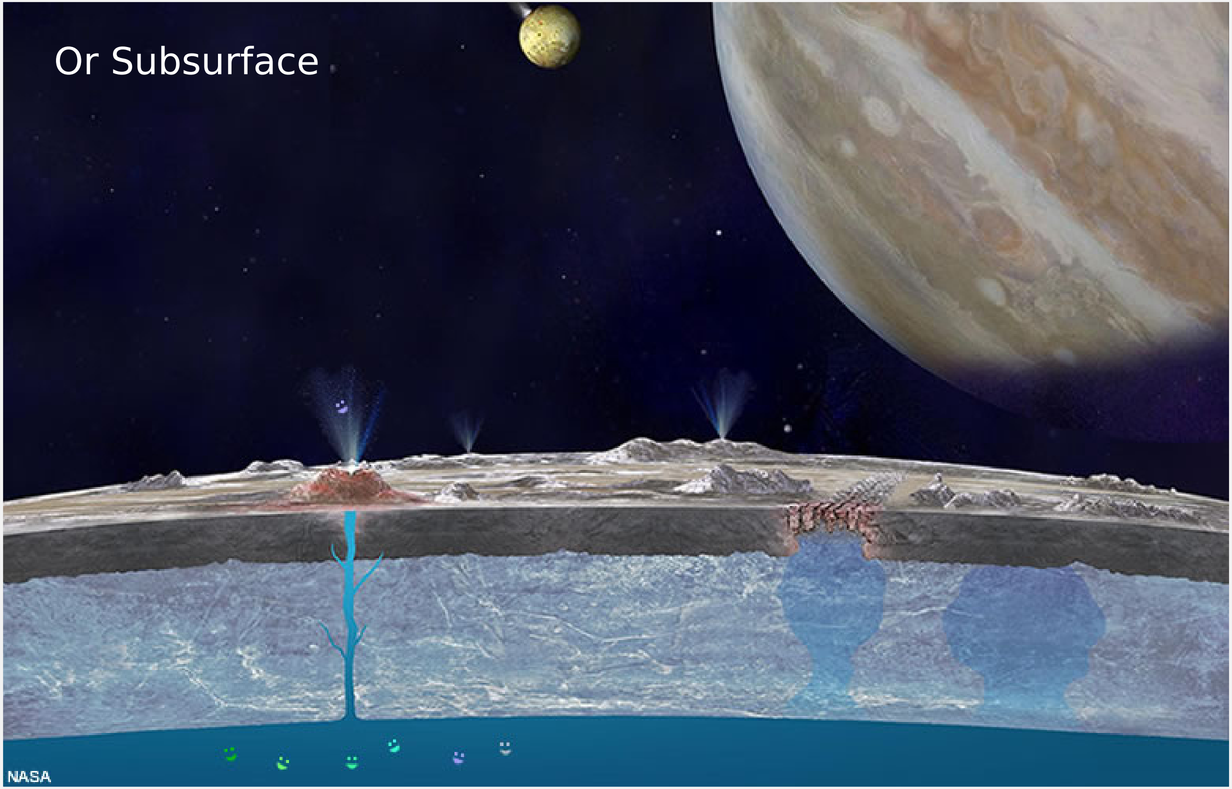




Feature	Approx. Value
Relief	800? m
Rim Diameter	9,500 m
Floor diameter	4,100 m
Rim slope	5?°

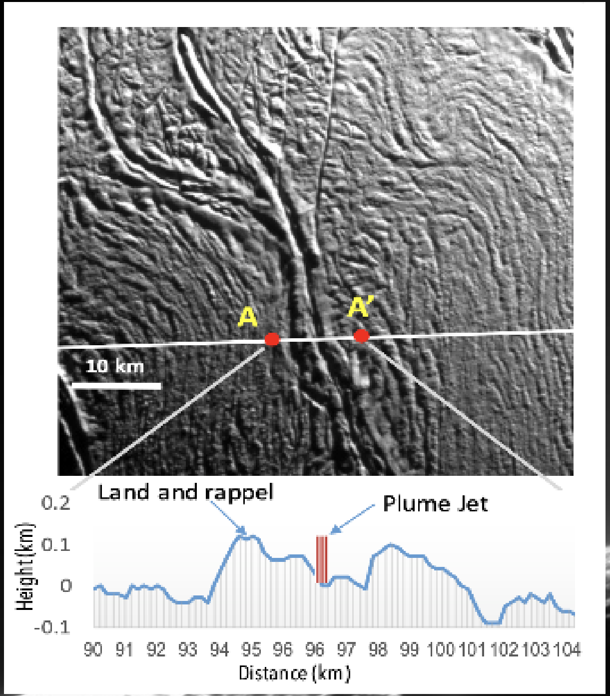
Feature for Traverse Route	Ascent	Descent
Average wall slope	20°	28°
Max wall slope	30°	36°
Minimum distance to RSL	1,200 m	360 m
Terrain type to wall	Polygonal ripples, sand dunes	Loose sand
Terrain type on wall	Loose sandy regolith, mixed/rocky sandy	Mixed rocky/ sandy terrain

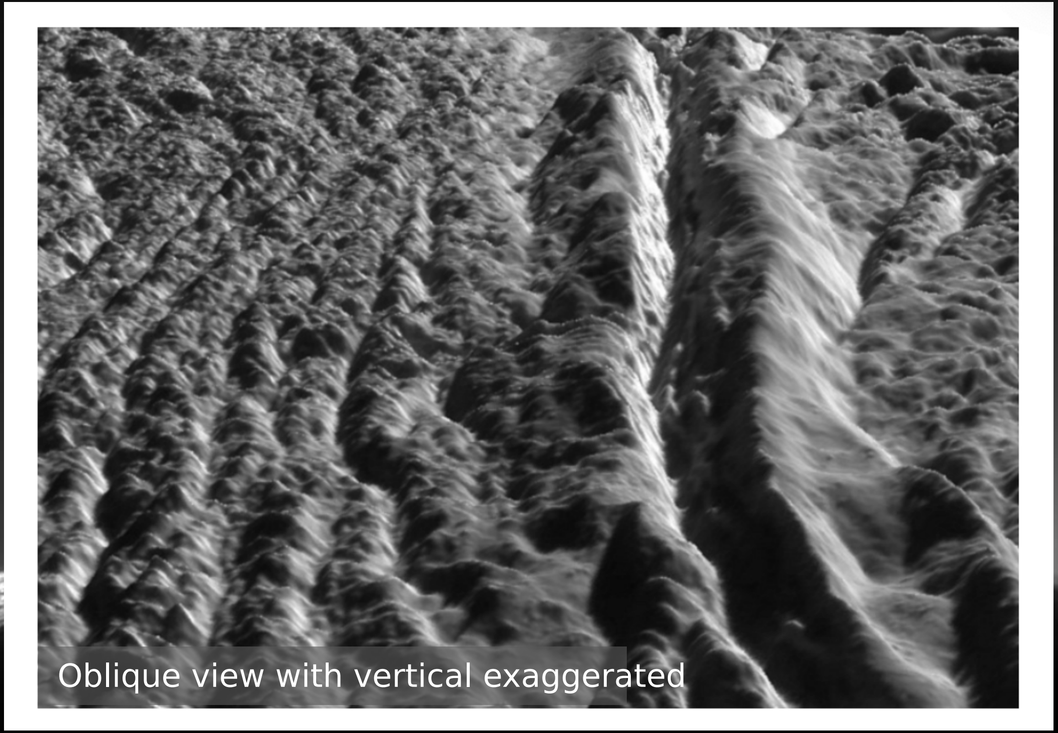
Europa


Or Subsurface

Artist’s concept of a Europa Plume

Enceladus





Oblique view with vertical exaggerated

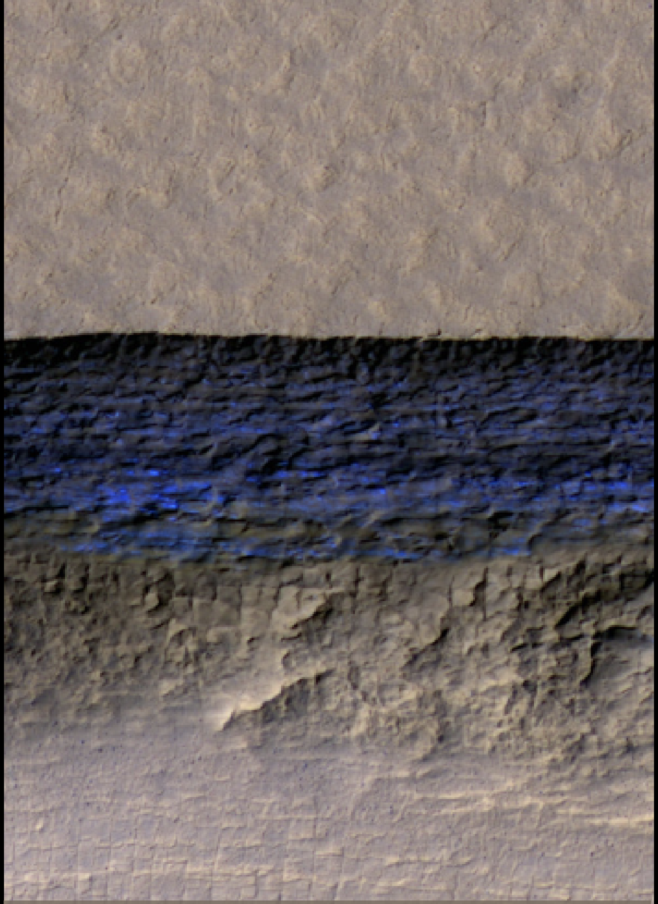
Plumes of icy particles, water vapor, and organics from Enceladus’ "tiger stripe" fissures near the south pole (from Cassini’s narrow-angle camera 2009; sun-phase angle 145°from 14,000 km from Enceladus; 81 m/pixel)

Credit: NASA/JPL-Caltech/Space Science Institute

Water Ice and Water?

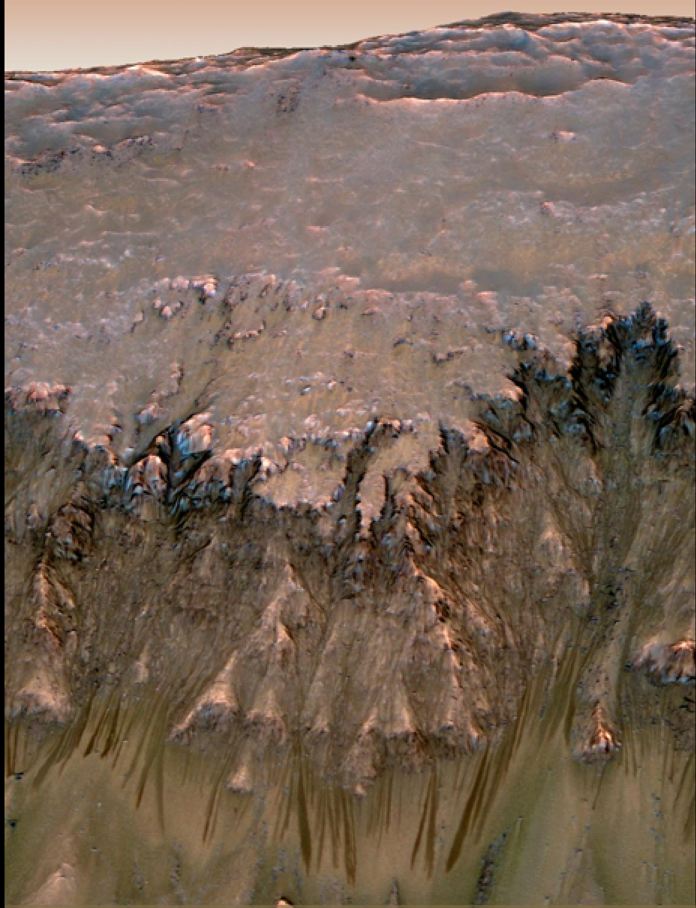
- Abundant in **polar ice caps** (on surface in the north and beneath the CO_2 ice cap in the south)
- Below **shallow subsurface** at more temperate conditions
- In **hydrated minerals**
- **Exposed water ice*** in scarps at mid latitudes
- **Deep** subsurface as ice or possibly in

*C. M. Dundas et al., "Exposed subsurface ice sheets in the Martian mid-latitudes," Science, 2018



Water Ice Deposits on Scarps

Steep slopes (45°– 55°) at mid-latitudes



Recurring Slope Lineae (flows)

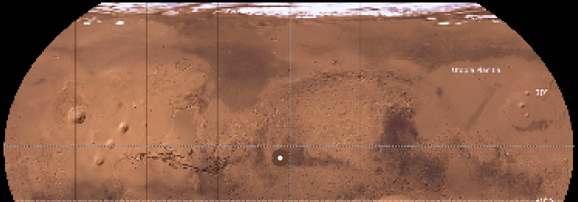
Steep slopes 25°– 40°

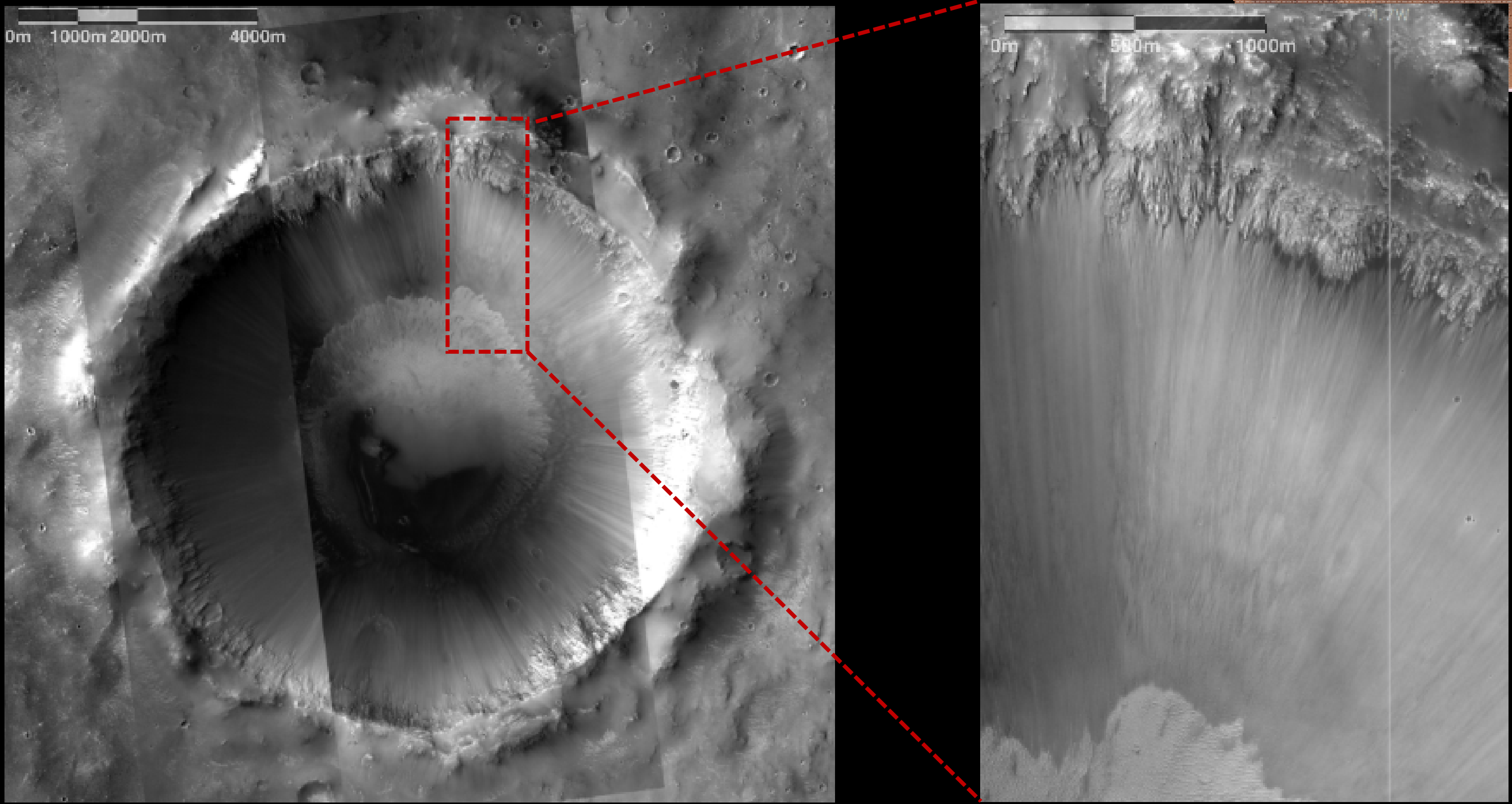
Credit: NASA/JPL-Caltech/UA/USGS

Recurring Slope Lineae: *Andapa Crater*

Elevation: -2,200 m Long/Lat: (-4.7, -5.3)

MMGIS

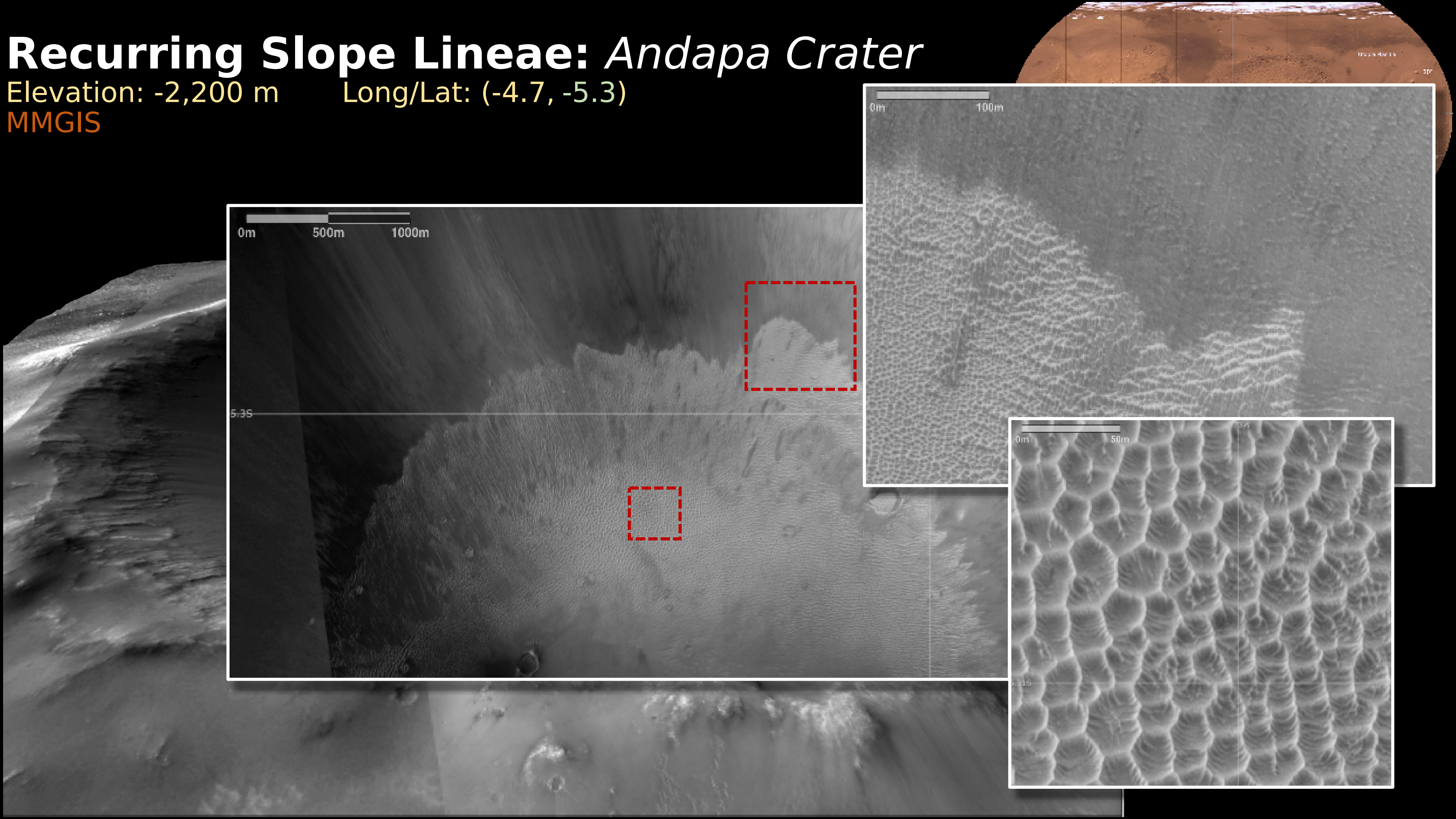




Recurring Slope Lineae: *Andapa Crater*

Elevation: -2,200 m Long/Lat: (-4.7, -5.3)

MMGIS



Recurring Slope Lineae: *Andapa Crater*

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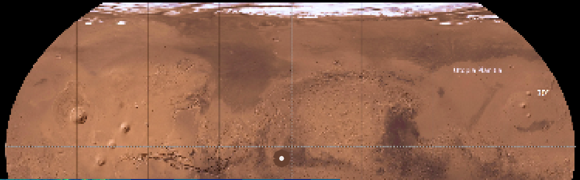
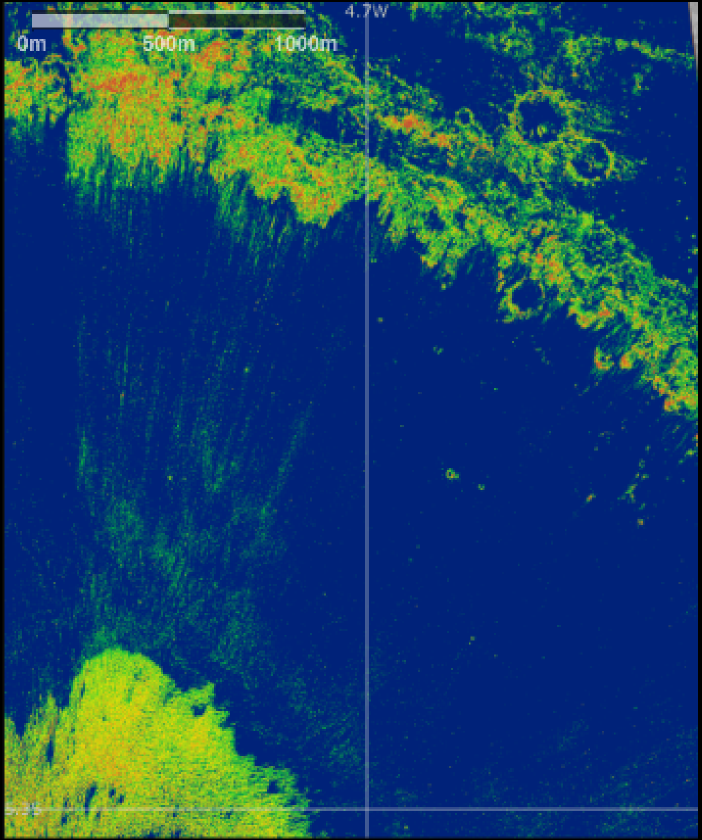
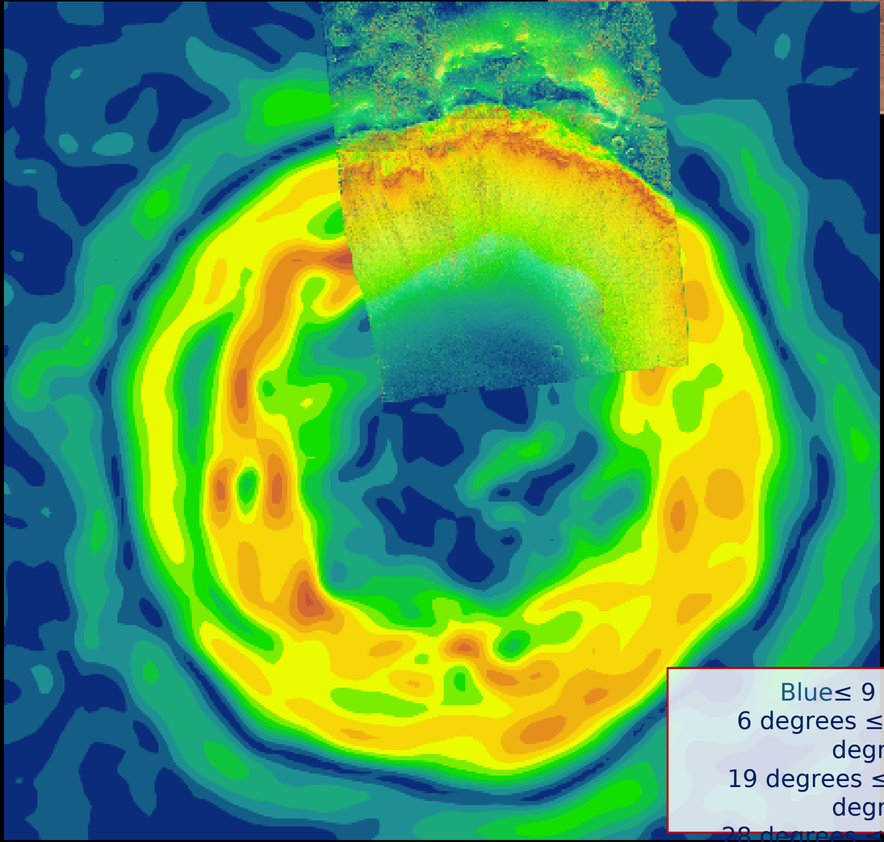
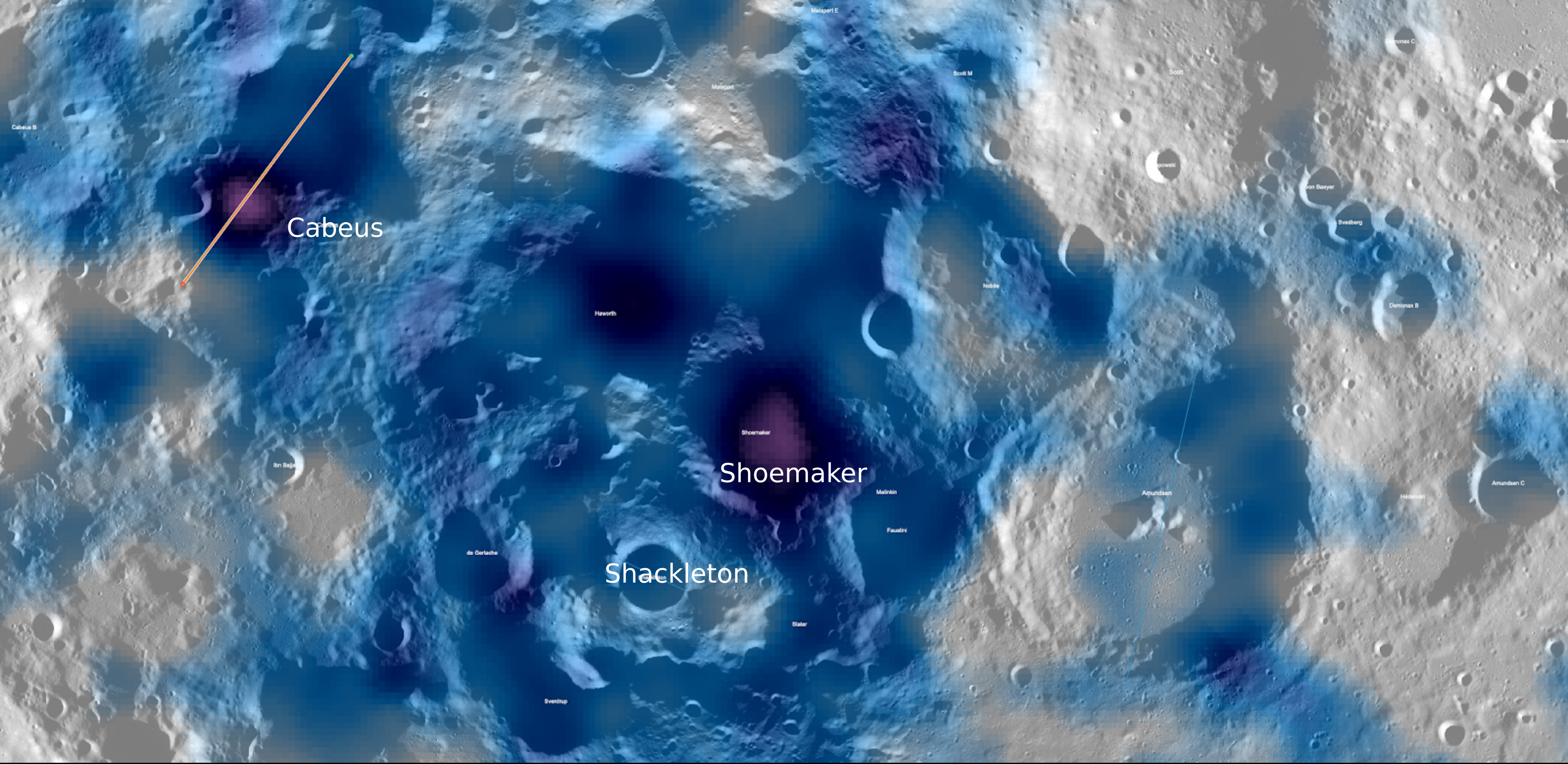






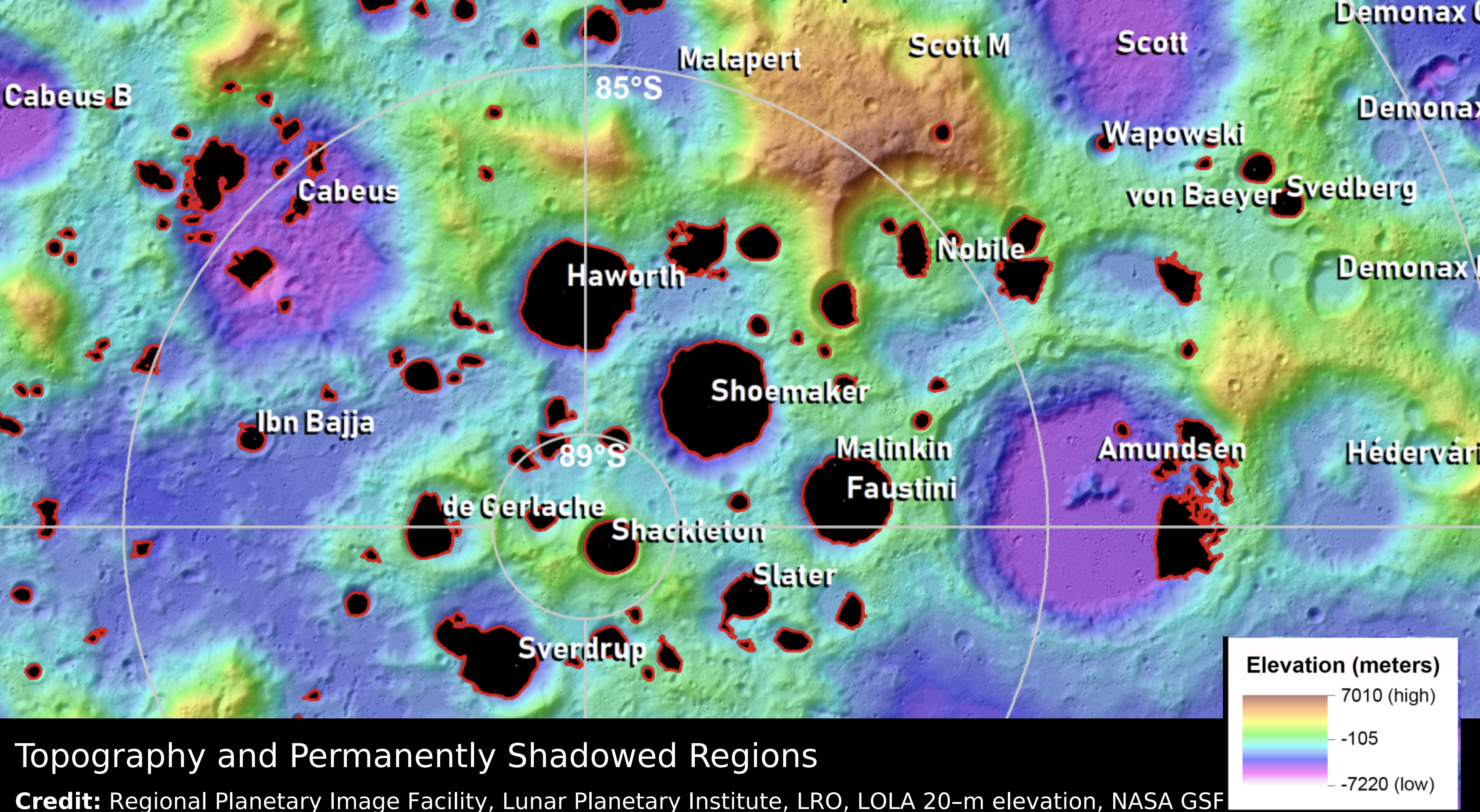
Blue≤ 9 degrees
6 degrees ≤ Green≤ 18 degrees
19 degrees ≤ Yellow≤ 27 degrees
28 degrees ≤ Orange≤ 33 degrees
Red ≥ 33 degrees



Hydrogen Abundance by Percent Weight in the Lunar South Pole

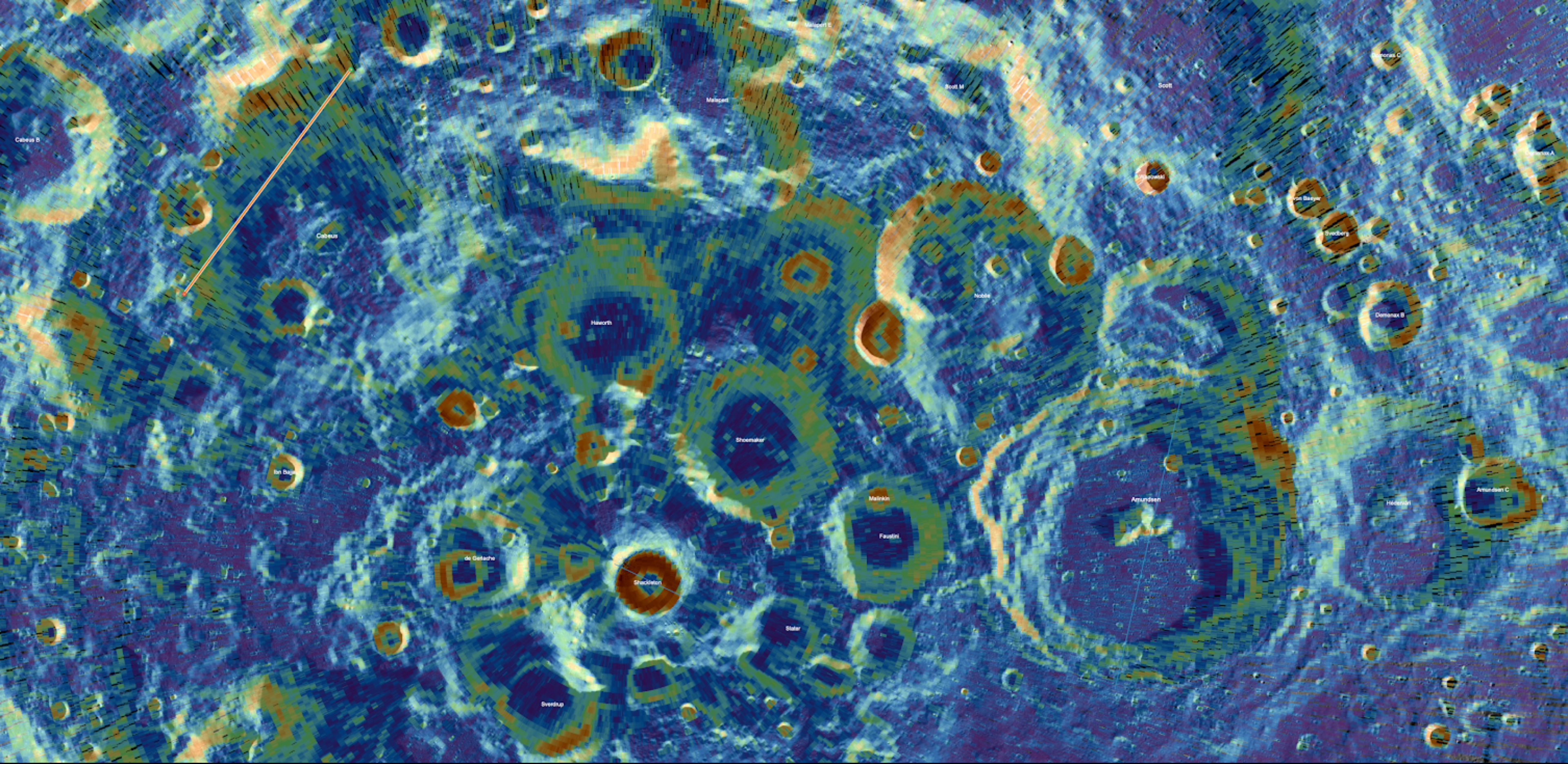
Credit: Lunar Exploration Neutron Detector (LEND) instrument on LRO

Sanin, A.B., et al., “Hydrogen distribution in the lunar polar regions,” Icarus, 2016



Topography and Permanently Shadowed Regions

Credit: Regional Planetary Image Facility, Lunar Planetary Institute, LRO, LOLA 20–m elevation, NASA GSF



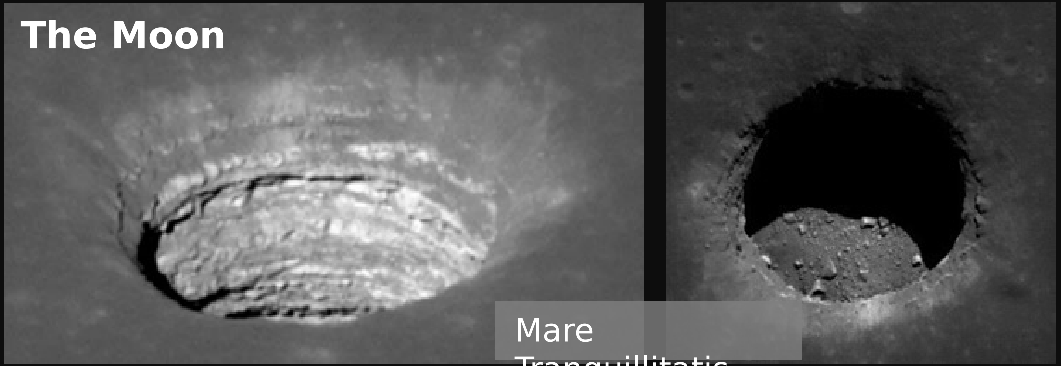
Slope Map of Permanently Shadowed Regions

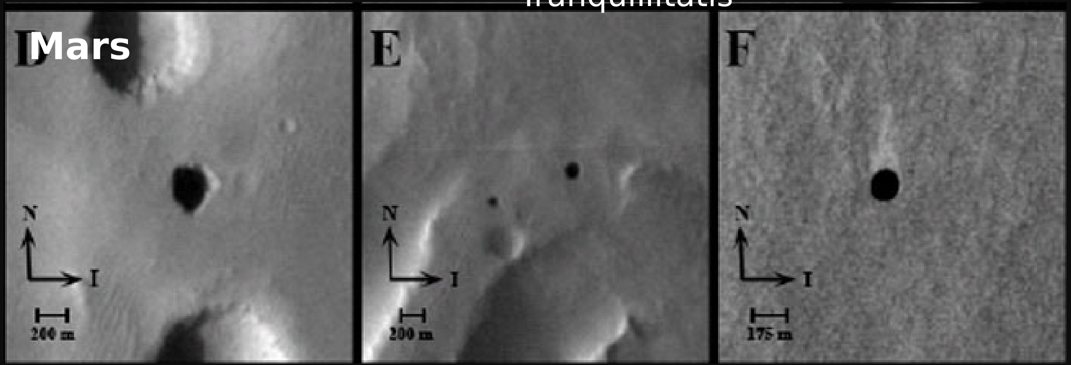
Credit: Regional Planetary Image Facility, Lunar Planetary Institute, LRO, LOLA 20–m elevation

Pits/Caves?

Skylights that could be openings to lava tubes

Vertical walls
No surface of repose





Credits:

- (Mars) G. Cushing, et al, (2007), THEMIS observes possible cave skylights on Mars, Geophysical Research Letters, 34
- (Moon) NASA/GSFC/Arizona State University
- (Earth) USGS, Hawaii and Arizona

Coming up

VIPER Rover (NASA ARC/JSC)

- **Instruments** to investigate polar volatiles
- **Subsurface access:** 1 m drill
- **Duration:** 100 Earth days
- **PSR operations:** hours to tens of hours
- **Size:** 430 kg, golf-cart size (~1.4 × 1.4 × 2 m^3)
- **Distance:** ~20 km
- **Speed:** 0.22 m/s
- **Launch date:** later 2023

Other funded surface developments

2021 US private: Astrobotic M1 carrying:
  - *Andy* CubeRover (CMU US)
  - *Unity* Team AngelicvM (Chile)
  - NASA CLPS payloads (US)
  - *Asagumo* Spacebit (UK)
  - Yaoki rover (Japan)

2021 India ISRO - Chandrayaan-3 rover

2021 Germany private: Audi Quattro lander and rover

2022 Japan JAXA SLIM pinpoint landing and roving

2023 US/Japan private (Draper/ispace) Hakuto-R