Mars Robotic and Human Landing Site Selection

Sydney Do, Ph.D. (Mars Program Formulation Office, NASA Jet Propulsion Laboratory, California Institute of Technology)

MIT AeroAstro 16.89 Lecture

Jet Propulsion Laboratory
California Institute of Technology

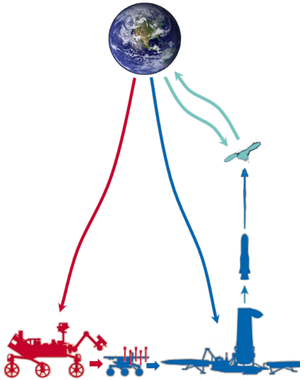
Personal Introduction

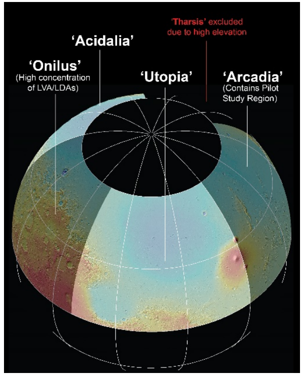
Jet Propulsion Laboratory
California Institute of Technology

Currently:

Systems Engineer, Mars Program Formulation Office, NASA JPL. Projects include:

- Joint NASA/ESA Mars Sample Return Formulation Team
- NASA Mars Human Landing Sites Study
  - Manager of Mars Water Mapping Projects
  - Mars Engineering Long Poles Teams for Reconnaissance and Logistics





Education

- PhD Space Systems (MIT AeroAstro 2016)
  - Research: Predicted logistics demands for different human Mars surface system architectures (ECLS, ISRU, habitation)
- S.M. Aeronautics and Astronautics (MIT AeroAstro 2011)
  - Research: Airbag-based Impact Attenuation Systems for the Orion MPCV
- B. Eng Aerospace (University of Sydney 2008)
  - Research: Satellite Formation Flight

Contents

Recent Policy Drivers for Human Missions to Mars

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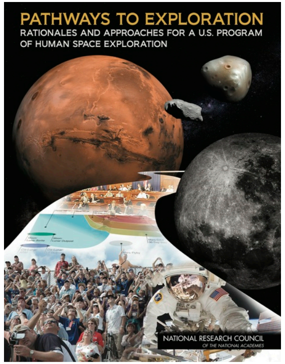
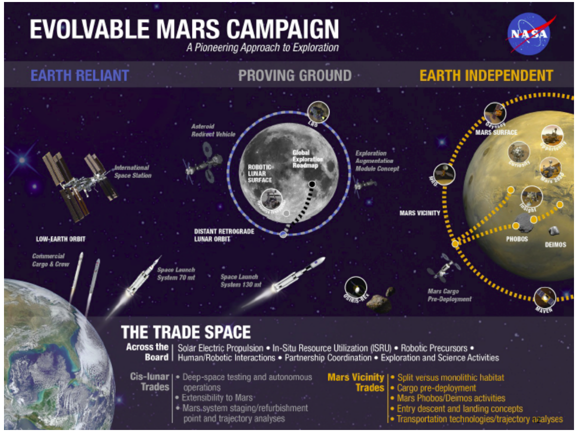
- **2010 NASA Authorization Act:** "The long term goal of the human space flight and exploration efforts of NASA shall be to expand permanent human presence beyond low-Earth orbit"
- **Fall 2012–June 2014**: National Academies Committee on Human Spaceflight studies sustainable paths forward for human spaceflight. Releases "Pathways to Exploration" Report, declaring that: "the 'horizon goal' for human space exploration is Mars"
- **April 2014**: NASA's "Journey to Mars" is announced, leads to the Evolvable Mars Campaign series of mission architecture studies
- **October 2015**: NASA releases "Journey to Mars" report, outlining the high level strategy and policy guidelines for developing a sustainable human Mars exploration program
- **NASA Transition Authorization Act of 2017**: "The key objectives of the United States for human expansion into space shall be… to achieve human exploration of Mars and beyond…"





The Past 60+ Years of Human Mars Mission Studies

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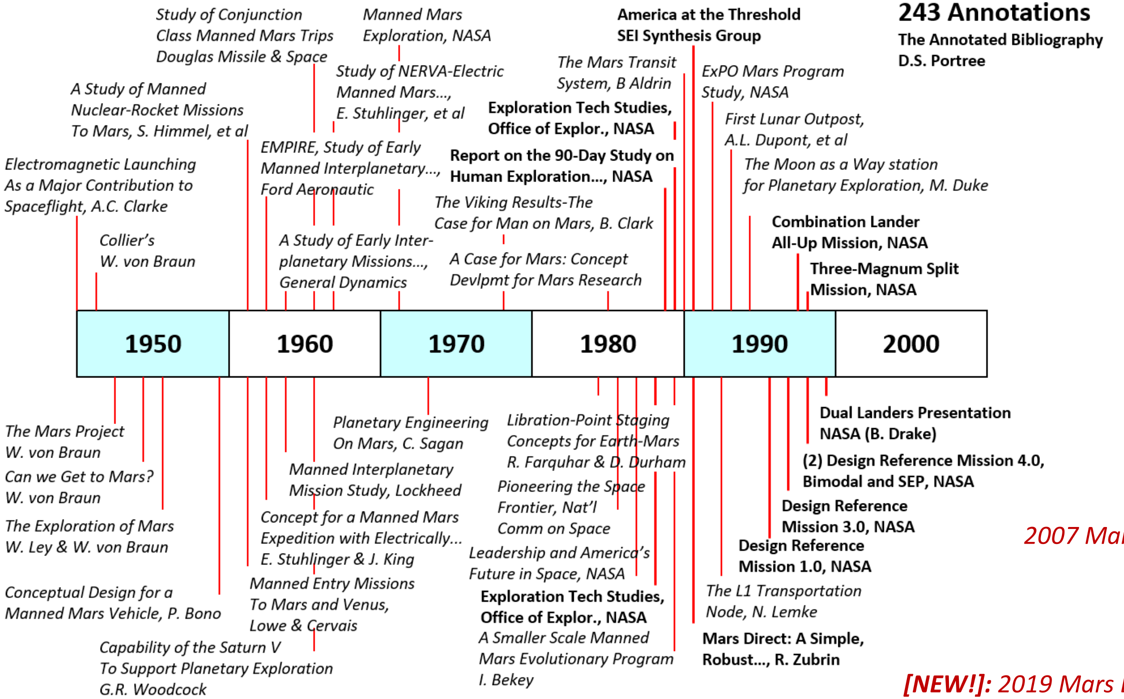
Overview of major Mars mission planning: 1950-2000



Major NASA Studies since 1988

1988: NASA "Case Studies"

1989: NASA "Case Studies"

1990: "90-Day" Study

1991: White House "Synthesis Group"

1992-93: NASA Mars DRM1.0

1998: NASA Mars DRM3.0

1998-2001: Associated DRM3.0 Analyses

2002-2004: DPT/NExT

2007 Mars Design Reference Architecture 5.0

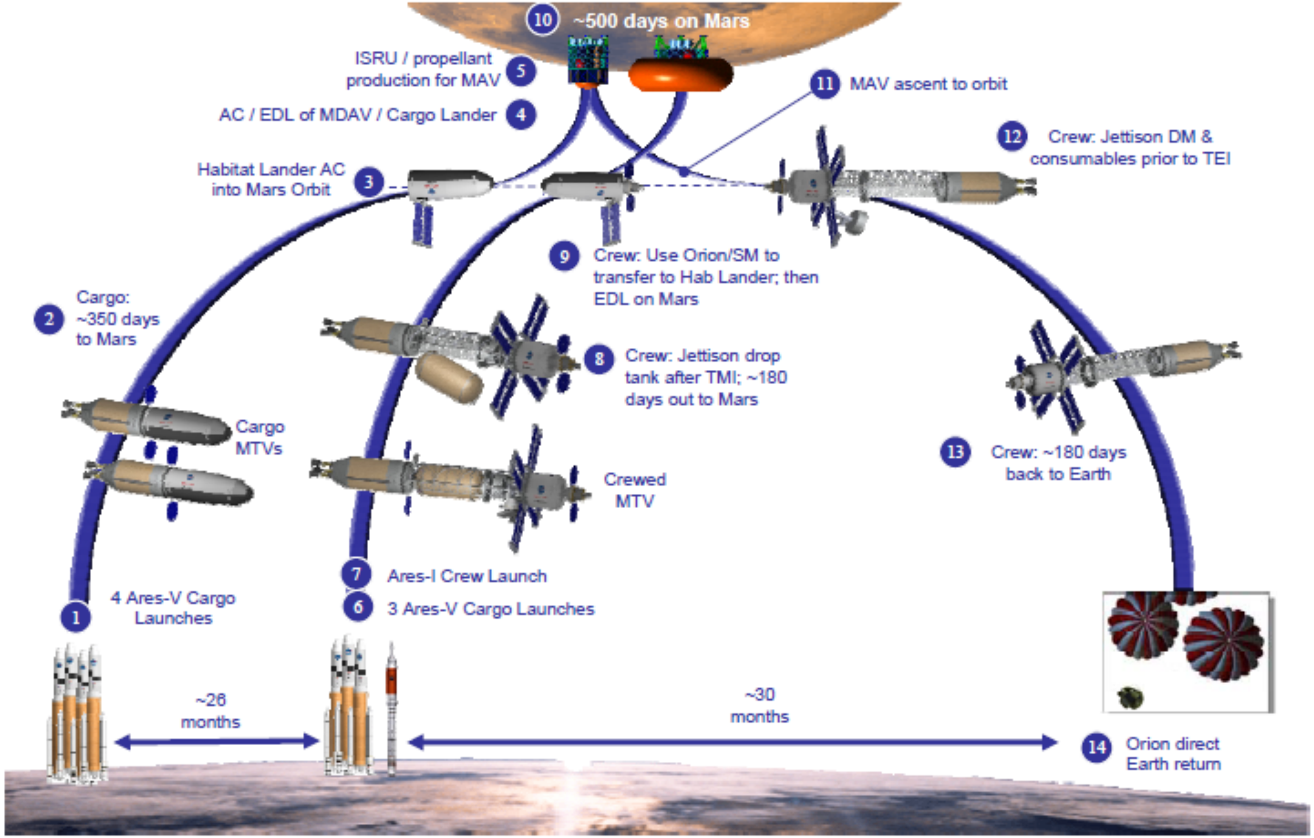
2009 Mars DRA5.0 Addendum

2014 Mars DRA5.0 Addendum #2

[NEW!]: 2019 Mars DRA6 (under production – summary of Evolvable Mars Campaign Study 2014-2017)

NASA Design Reference Architecture 5.0

Jet Propulsion Laboratory
California Institute of Technology



Evolution of Mars Mission Architecture Concepts

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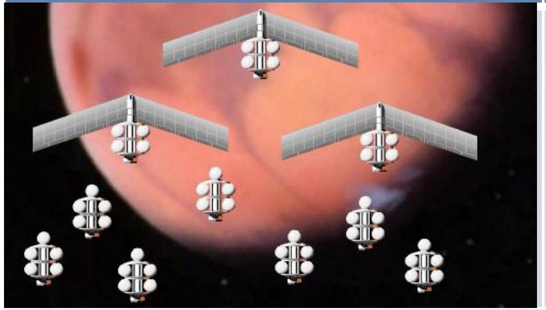
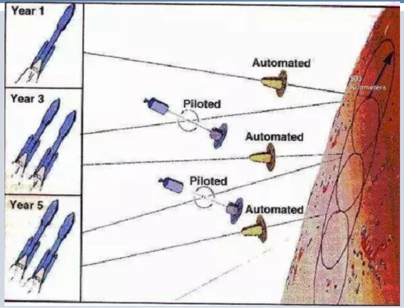
California Institute of Technology

Das Marsproject (von Braun, 1952)

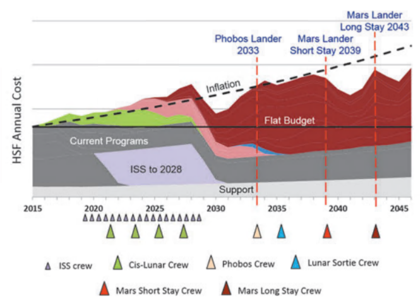


Mars Direct (Baker & Zubrin 1990)

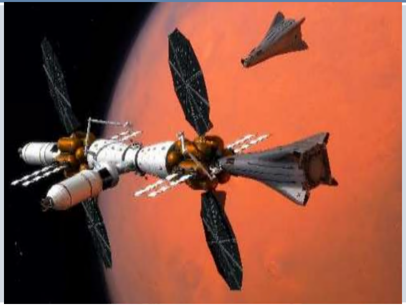


NASA DRA 5.0 (2007, ADD2 2014)

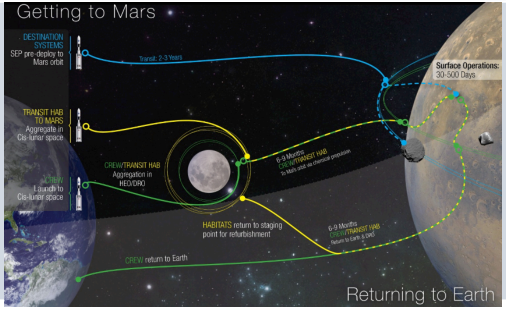
JPL Minimal Mars (2015)



LM Mars Basecamp (2016)



NASA EMC (2014-2016)



Evolution of Mars Mission Architecture Concepts

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	Das Marsproject (von Braun, 1952)	Mars Direct (Baker & Zubrin 1990)	NASA DRA 5.0 (2007, ADD2 2014)	JPL Minimal Mars (2015)	LM Mars Basecamp (2016)	NASA EMC (2014-2016)
No. Crew	70; 50 to surface	4 to surface	6 to surface	4; 2 to surface	6; 4 to surface	4 to surface
Pressu-rized Elements	3 winged landers + 7 crew and cargo transporters	Earth Return Vehicle with integrated ISRU, Transit/ Surface Hab	MAV+ISRU, Surface Hab (SHAB), MTV, Orion	DSH, DSH resupply module, Orion, DAV	Orion, Mars Basecamp, Reusable DAV	MAV+ISRU, Surface Hab, DSH, Orion
Class	Conjunction	Conjunction	Conjunction	Conjunction	Conjunction	Conjunction
Surf. Stay	400 days	~500 days	~500 days	24 days	~14 days	~500 days
Outbound Aggregati on Point?	All S/C assembled in LEO via reusable shuttles	None – Direct launch of everything to surface	SHAB & MAV assembled & injected together from LEO; separate in HMO	HMO – crew in DSH dock with DAV	Basecamp assembled in HEO before SEP tugged to 1-sol HMO	DSH and Orion at Gateway in Lunar NHRO
Predeploy ed Elements	None – all up mission	Earth Return Vehicle with integrated ISRU	MAV+ISRU to surface, SHAB with Logistics to HMO	MAV boost stage to LMO; DSH resupply module, DAV, & TEI stage to HMO	Entire Mars Basecamp (a small space station in HMO) via SEP	MAV+ISRU to, surface hab+logistics
ISRU	None	Atmospheric: Carry H2 – create CH_4 & O_2	Atmospheric for MAV O_2, carry CH_4 for MAV, carry H_2 for ECLS	None	None – MAV refueled by LOX/LH2 delivered from Earth	Atmospheric for MAV O_2, initially carry CH_4, soil based up for trade
Landing Site	Polar crew lands, goes to equator to prepare for equatorial landings	Unspecified equatorial, different for each mission (320km apart)	Unspecifed – different for each mission	Unspecified	Unspecified – sortie missions to multiple sites	Jezero Crater eg. Site. Expl. Zone concept studied
Comment s	Inspired by Antarctic Exploration	Reaction to 90 Day Study that canceled SEI	Evolved from Mars direct – 1st to trade surface architectures. Uses NTR	Minimizes new developments, designed to cost	First Mars space station concept for multiple surface sorties	NHRO aggregation and refurbishment point for DSH

The Past 60+ Years of Human Mars Mission Studies

Jet Propulsion Laboratory
California Institute of Technology

Overview of major Mars mission planning: 1950-2000

Study of Conjunction Class Manned Mars Trips Douglas Missile & Space

Manned Mars Exploration, NASA

America at the Threshold SEI Synthesis Group

243 Annotations
The Annotated Bibliography
D.S. Portree

A Study of Manned Nuclear-Rocket Missions To Mars, S. Himmel, et al

Study of NERVA-Electric Manned Mars..., E. Stuhlinger, et al

The Mars Transit System, B Aldrin

ExPO Mars Program Study, NASA

Exploration Tech Studies, Office of Explor., NASA

First Lunar Outpost, A.L. Dupont, et al

Electromagnetic Launching As a Major Contribution to Spaceflight, A.C. Clarke

EMPIRE, Study of Early Manned Interplanetary..., Ford Aeronautic

Report on the 90-Day Study on Human Exploration..., NASA

The Moon as a Way station for Planetary Exploration, M. Duke

Collier's W. von Braun

planetary Missions..., General Dynamics

A Case for Mars: Concept Devlmt for Mars Research

Three-Magnum Split Mission, NASA

1950	1960	1970	1980	1990	2000

The Mars Project W. von Braun

Can we Get to Mars? W. von Braun

The Exploration of Mars W. Ley & W. von Braun

Conceptual Design for a Manned Mars Vehicle, P. Bono

Capability of the Saturn V To Support Planetary Exploration G.R. Woodcock

Planetary Engineering On Mars, C. Sagan

Manned Interplanetary Mission Study, Lockheed

Concept for a Manned Mars Expedition with Electrically... E. Stuhlinger & J. King

Manned Entry Missions To Mars and Venus, Lowe & Cervais

Libration-Point Staging Concepts for Earth-Mars R. Farquhar & D. Durham

Pioneering the Space Frontier, Nat'l Comm on Space

Leadership and America's Future in Space, NASA

Exploration Tech Studies, Office of Explor., NASA

A Smaller Scale Manned Mars Evolutionary Program I. Bekey

Dual Landers Presentation NASA (B. Drake)

(2) Design Reference Mission 4.0, Bimodal and SEP, NASA

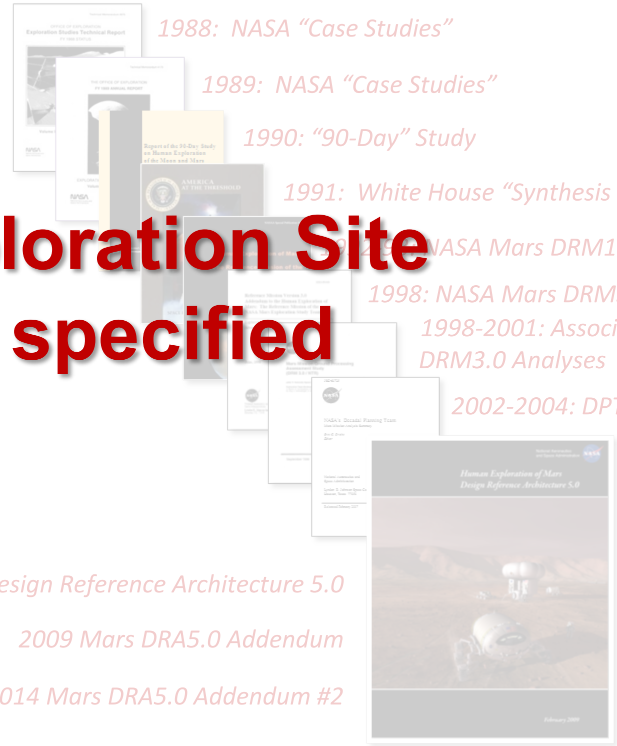
Design Reference Mission 3.0, NASA

Design Reference Mission 1.0, NASA

The L1 Transportation Node, N. Lemke

Mars Direct: A Simple, Robust..., R. Zubrin

Major NASA Studies since 1988



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2002-2004: DPT/NExT

2007 Mars Design Reference Architecture 5.0

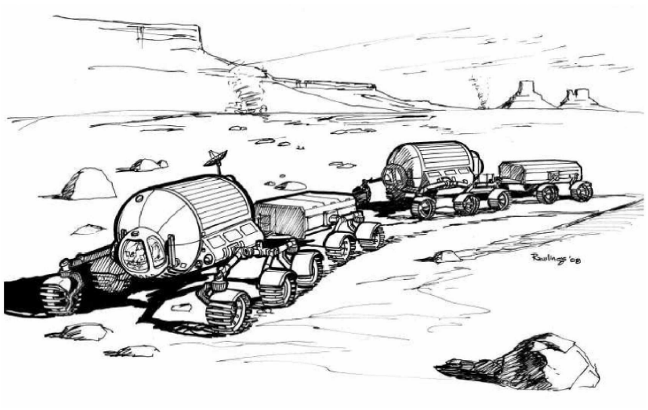
2009 Mars DRA5.0 Addendum

2014 Mars DRA5.0 Addendum #2

Specific Landing and Exploration Site on Mars not studied or specified

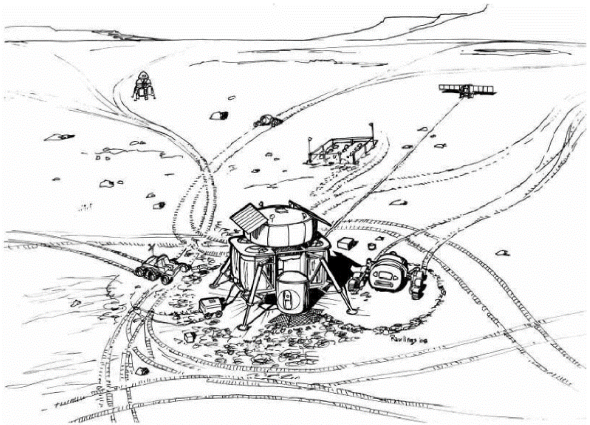
NASA Design Reference Architecture 5.0
Surface Architecture Trades

Mobile Home



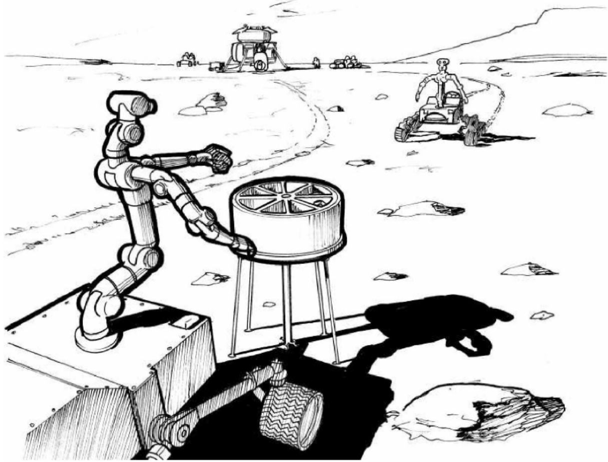
Baselined During Constellation Program

Commuter



Baselined for NASA DRA5.0 and EMC

Telecommuter



Crew perform short distance EVAs. Robots do long distance exploration

Human Spaceflight Architecture Decision Graph
(Do PhD 2016)

Jet Propulsion Laboratory
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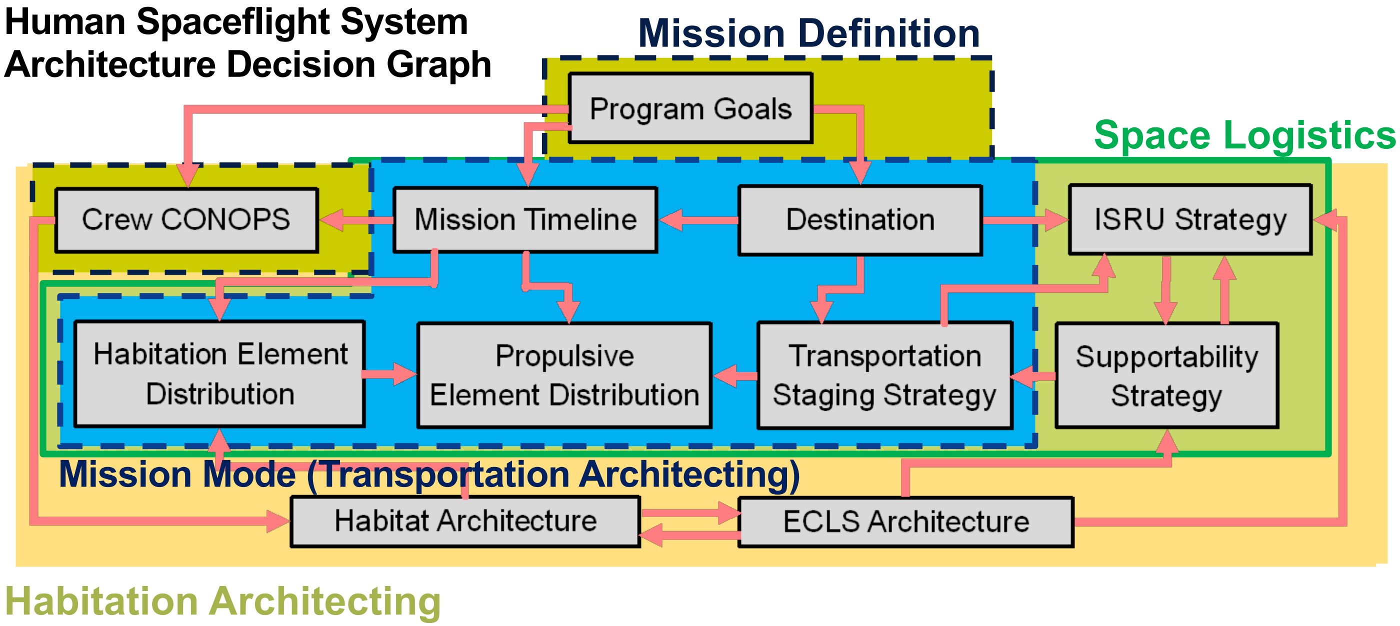
Research Question:
What set of coupled technologies and operational strategies are required to develop a sustained human presence on the surface of Mars?



Landing Site Selection for Robotic Missions

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Mars Exploration Program

20+ years of continuous robotic exploration of Mars

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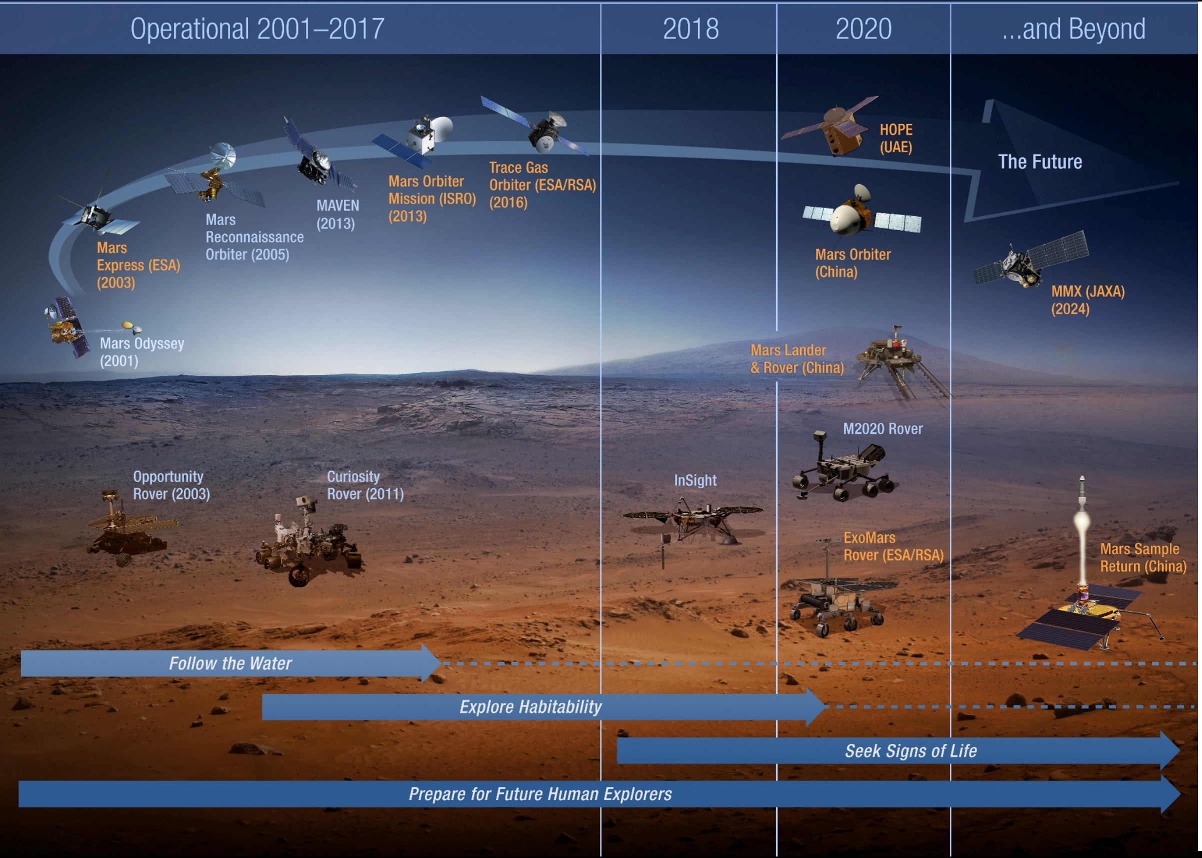
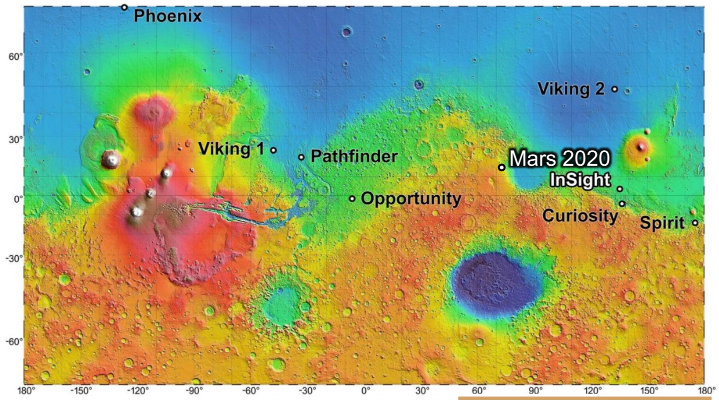
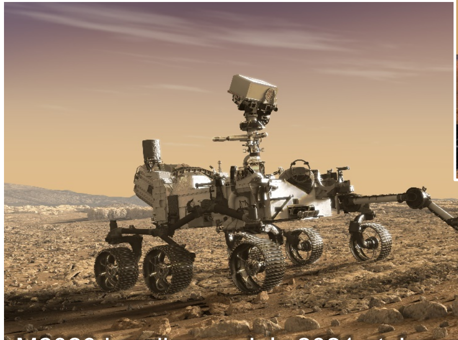


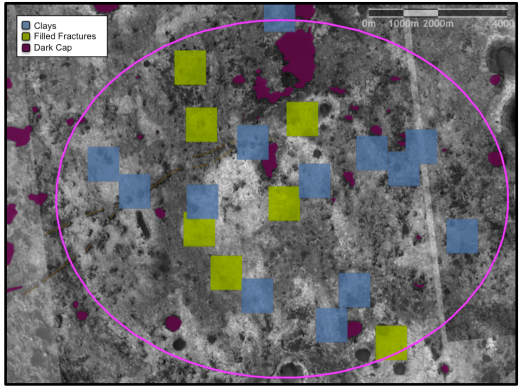


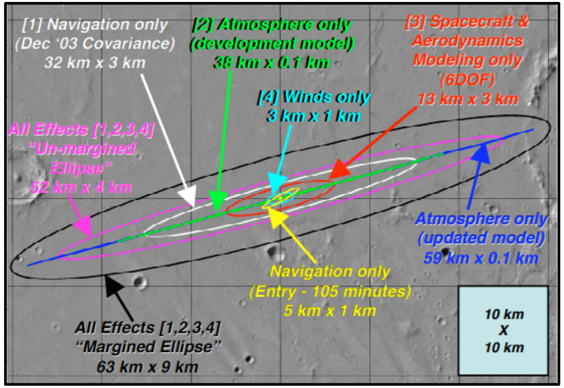


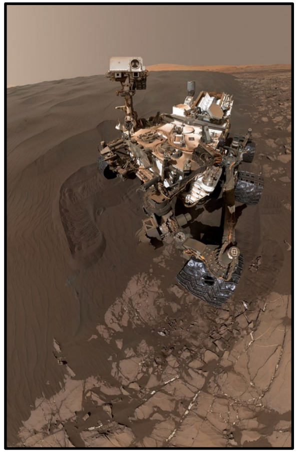
M2020 Landing on July 2021 at Jezero Crater will cache 20-40 samples for potential return by a future mission

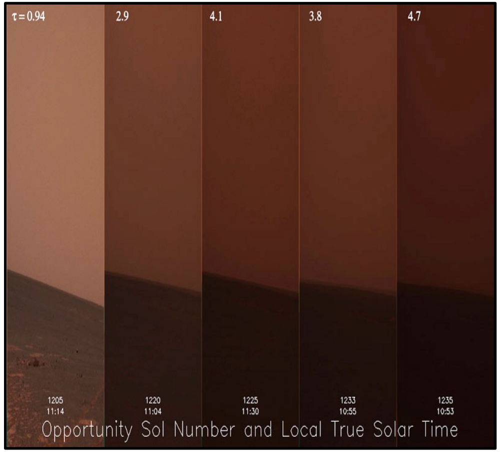
Landing Site Selection for Mars Rover Missions

- **Driven primarily by science value**
  - Maximize number and diversity of science regions of interest
- **Engineering constraints**
  - Landing safety
    - Atmospheric temperature and pressure, winds, site altitude, local rock distribution, slope of local terrain, lighting
  - Rover survival
    - Landing site season, insolation, likelihood of dust storms
  - Rover traversability
    - Rock distribution, slopes, terrain type





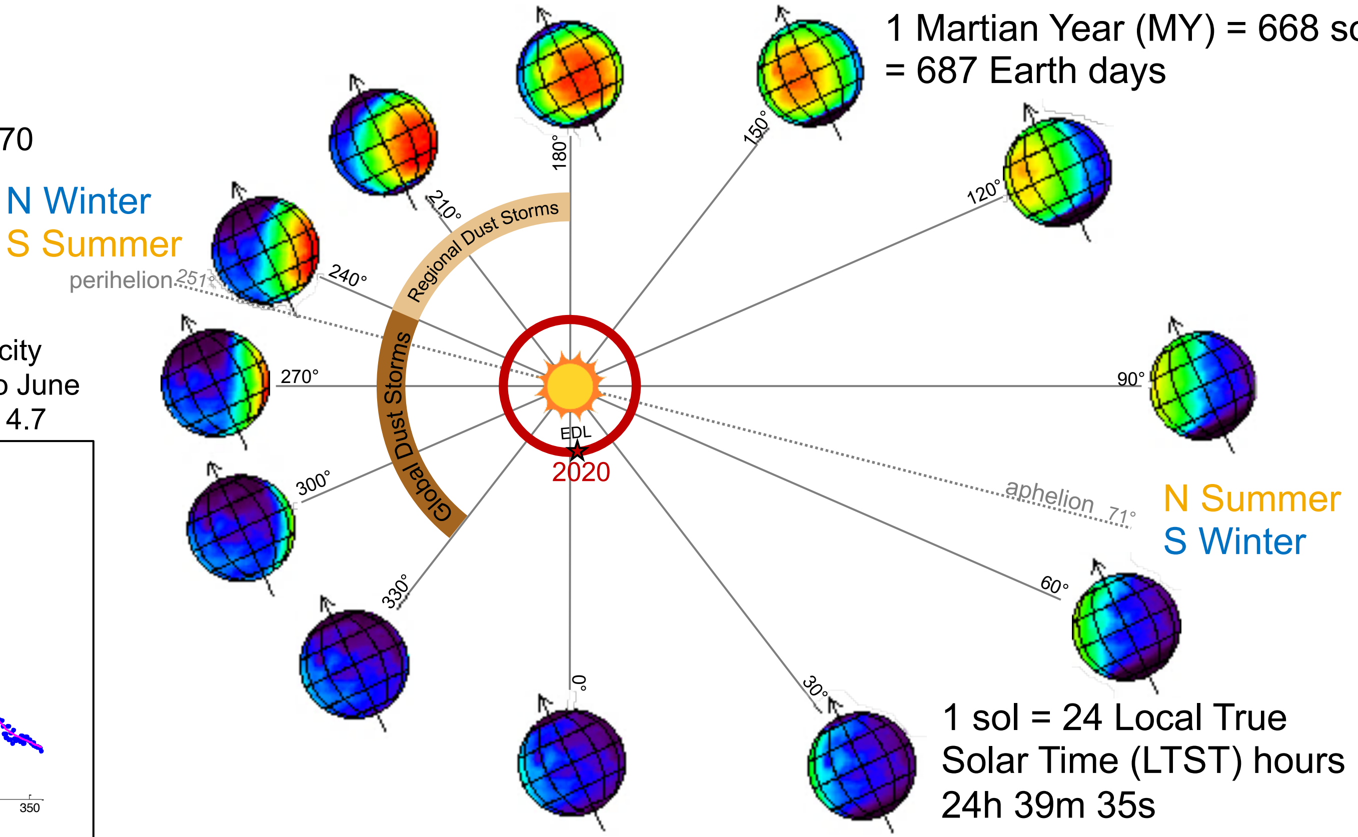




Martian Seasons and Dust Storms – Critical for Solar Only Missions

Global/regional dust storms:

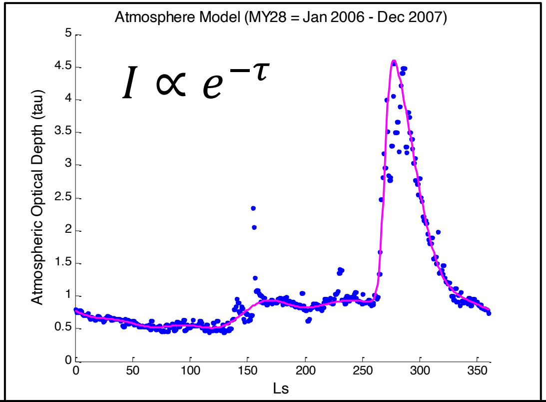
- Occur approximately once in every 3 Martian years
- Can start between Ls ~180 to 270
- Take a month or longer to settle to τ<~2.0 (i.e. dust settling period)



1 Martian Year (MY) = 668 sols = 687 Earth days

1 sol = 24 Local True Solar Time (LTST) hours = 24h 39m 35s

Worst Case Atmospheric Opacity During Global Dust Storm Prior to June 2018 Dust Storm Event: τ_{max} = 4.7

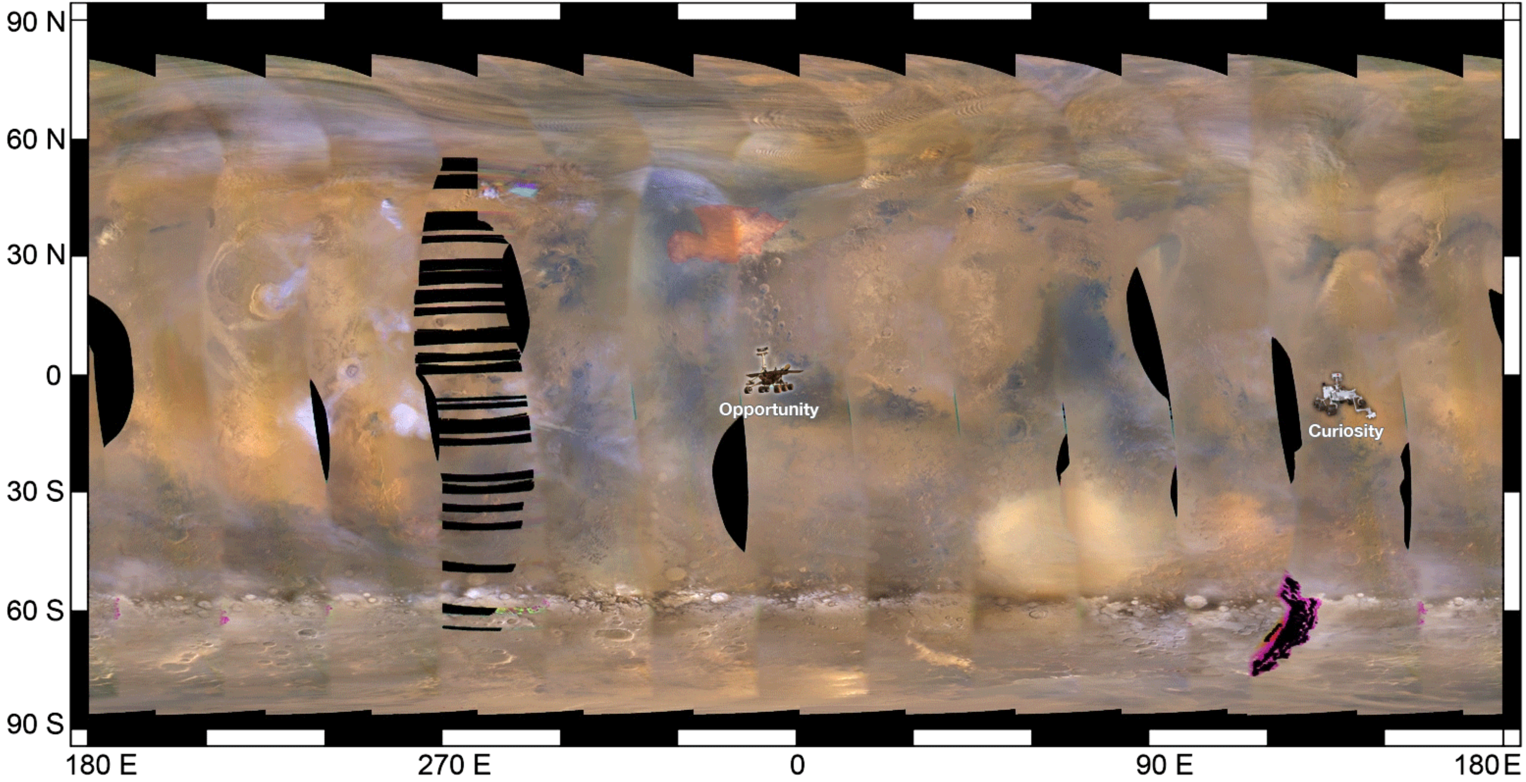


Unprecedented Global Dust Storm Starts Late May 2018 (Ls 185°)

Jet Propulsion Laboratory
California Institute of Technology

Images from MRO Mars Color Imager (MARCI)

May 31 - June 11, 2018



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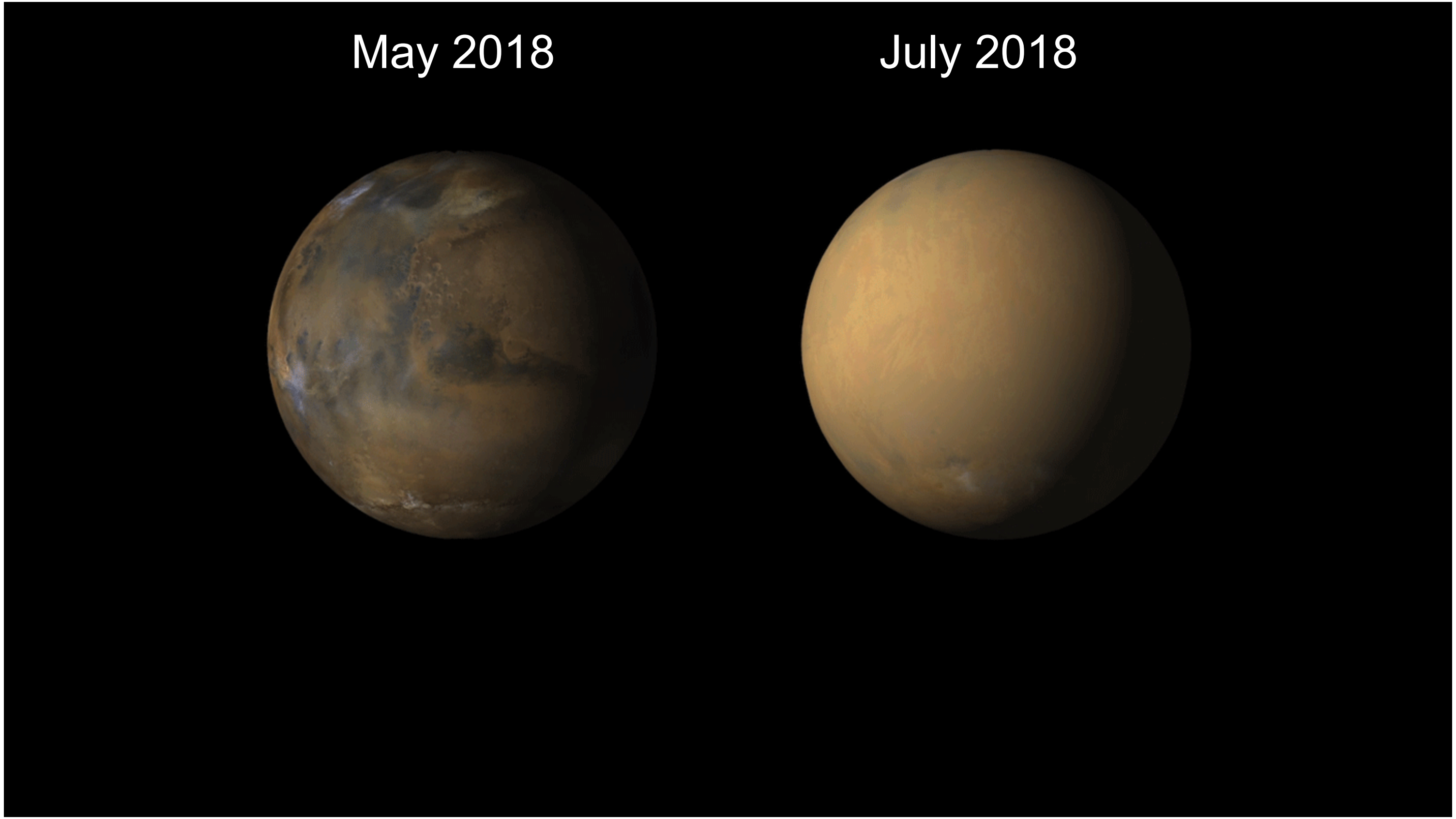
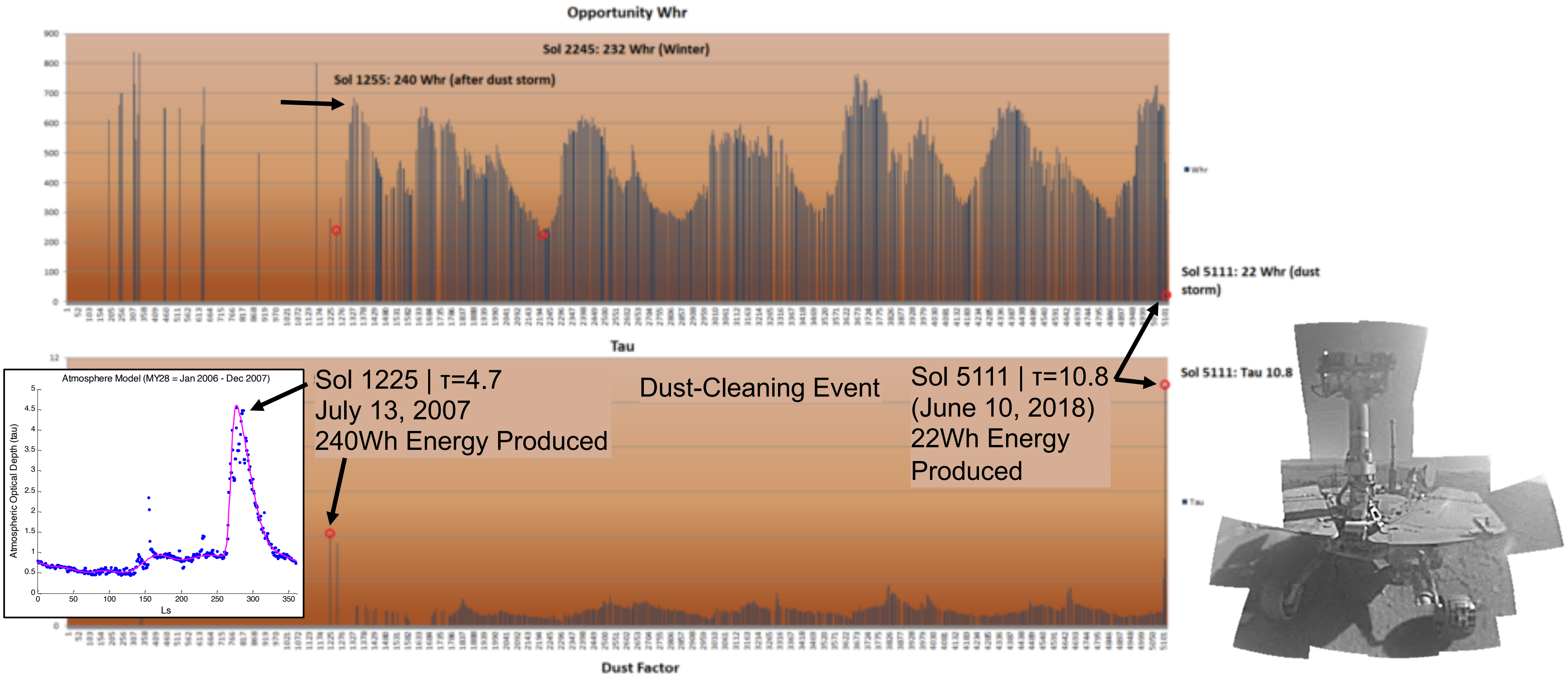


Opportunity Rover Lifetime Power Production

Jet Propulsion Laboratory
California Institute of Technology



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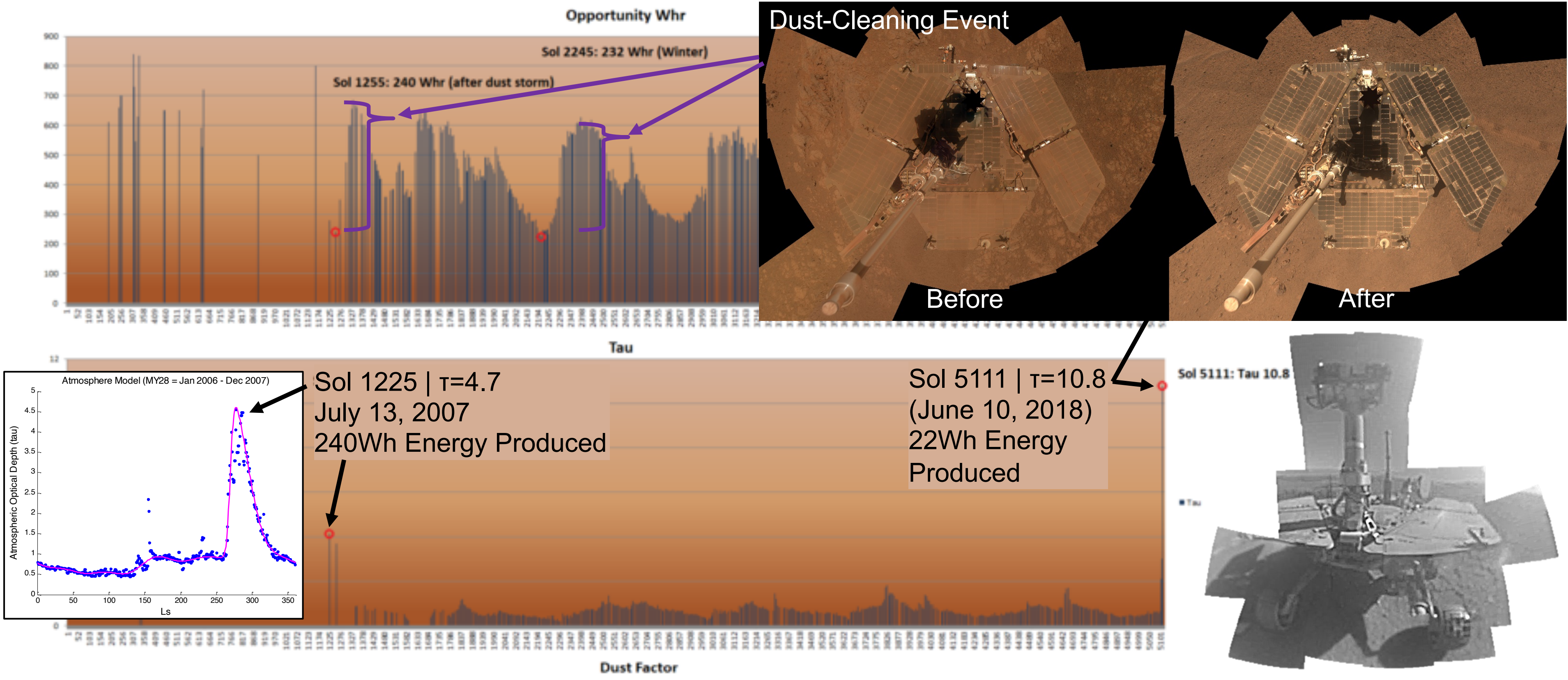
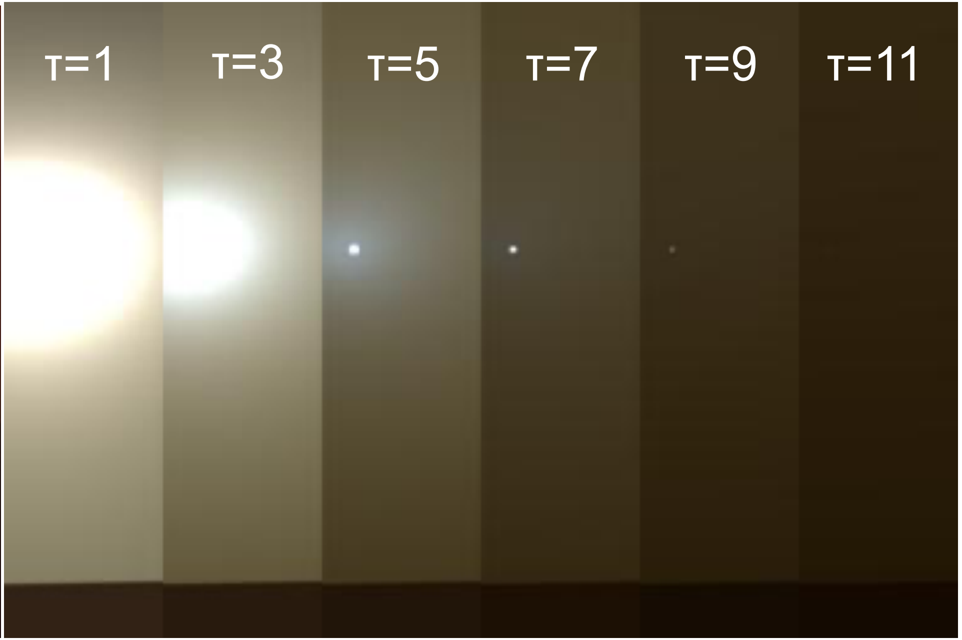


Optical Depth as Viewed from the Surface

Photos Taken by Opportunity

Simulated



Cumulative Fractional Area (CFA) Definition

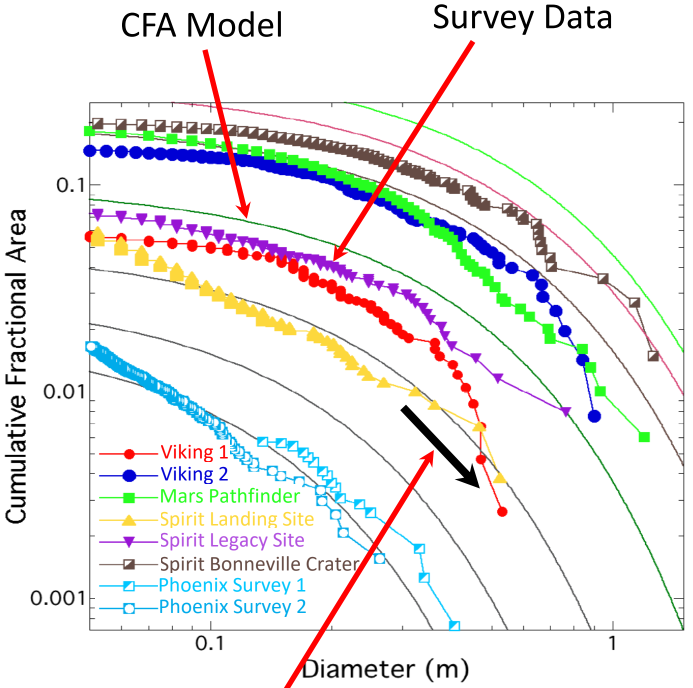
Jet Propulsion Laboratory
California Institute of Technology

- General model of rockiness of a site (applicable to Earth and Mars)
  - Based on analysis of Mars orbital data, Mars surface imagery, field surveys on Earth, and geologic fracture and fragmentation theory
- Represents the cumulative distribution of rock diameter at a site, based on the exponential relationship:

$$CFA_k(D) = k \cdot exp\left[-\left(1.79 + \frac{0.152}{k}\right) D\right]$$

Where:

- ***$CFA_k(D)$*** is the **cumulative fractional area** of some region covered by rocks of **diameter *D* or larger**
- ***k*** is the **rock abundance**, or the fraction of the total area covered by rocks (note that $k = CFA_k(0)$)



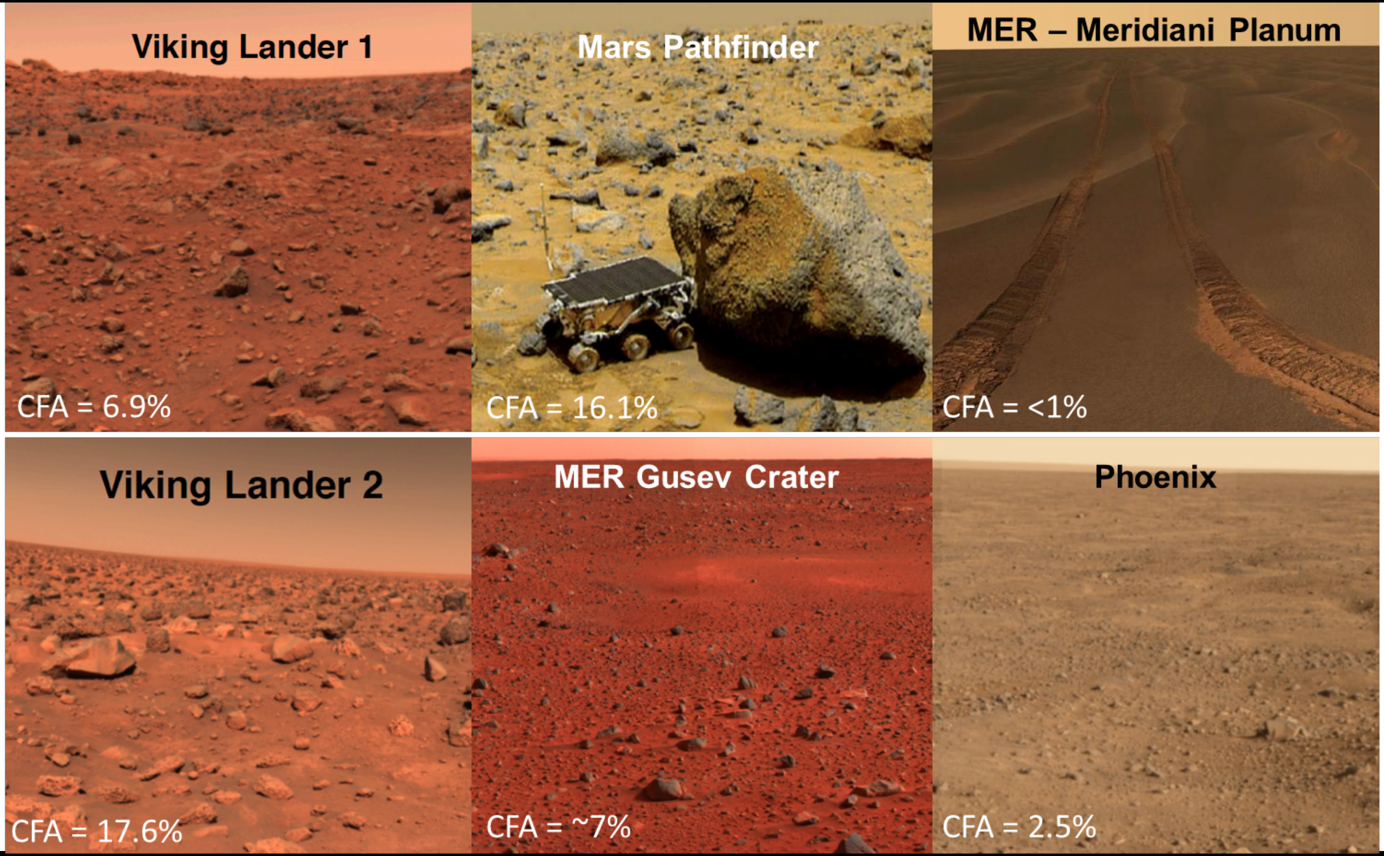
Presence of rocks decreases exponentially with increasing rock diameter

-Golombek, M., Rapp, D., 1997, Size-frequency distributions of rocks on Mars and Earth analog sites: Implications for future landed missions, Journal of Geophysical Research, Vol. 102, No. E2, pp. 4117-4129, February 25, 1997

-Golombek, M., Huertas, A., Kipp, D., Calef, F., 2012, Detection and Characterization of Rocks and Rock Size-Frequency Distributions at the Final Four Mars Science Laboratory Landing Sites, The International Journal of Mars Science and Exploration, Vol. 7, pp. 1-22, doi: 10.1555/mars.2012.0001

Cumulative Fractional Area (CFA)

Jet Propulsion Laboratory
California Institute of Technology



Mars 2020 Landing Site Selection Process

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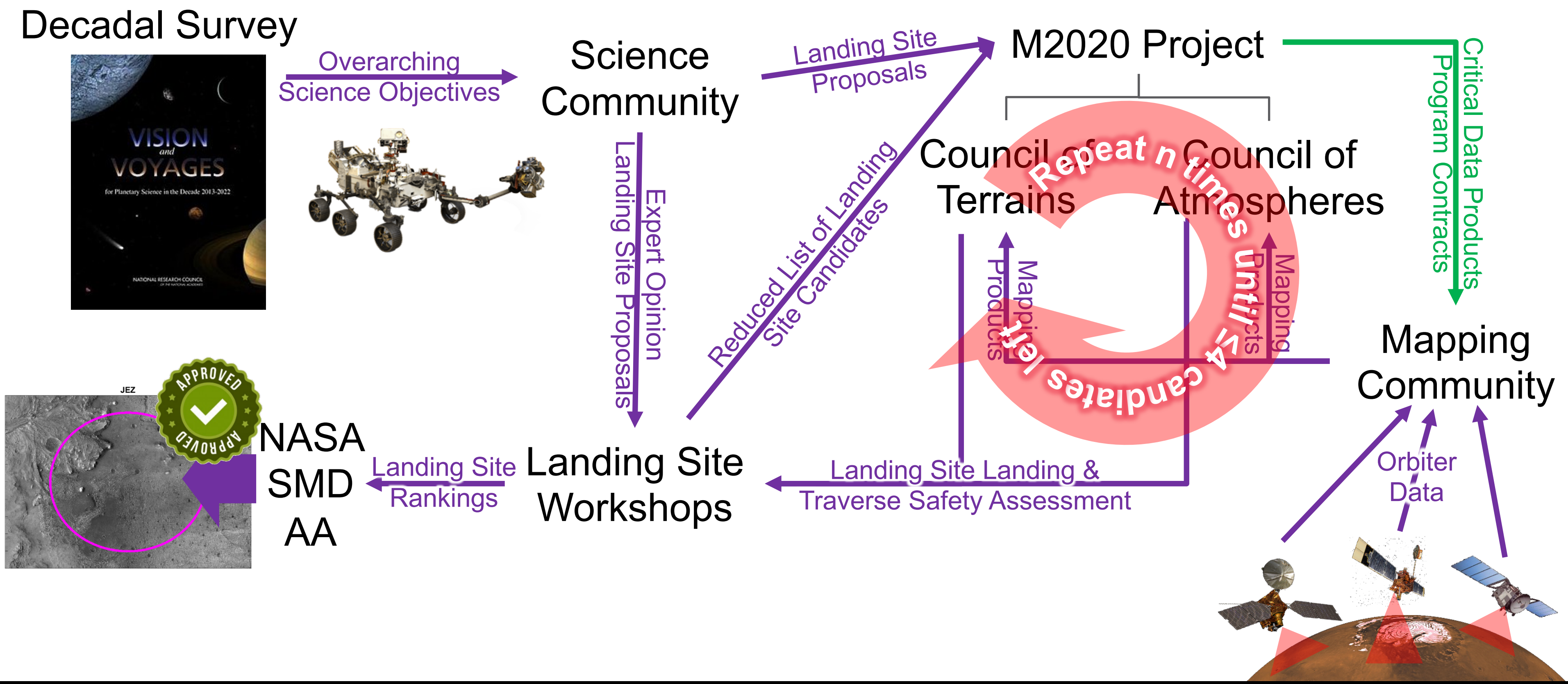
California Institute of Technology



Mars 2020 Science Objectives

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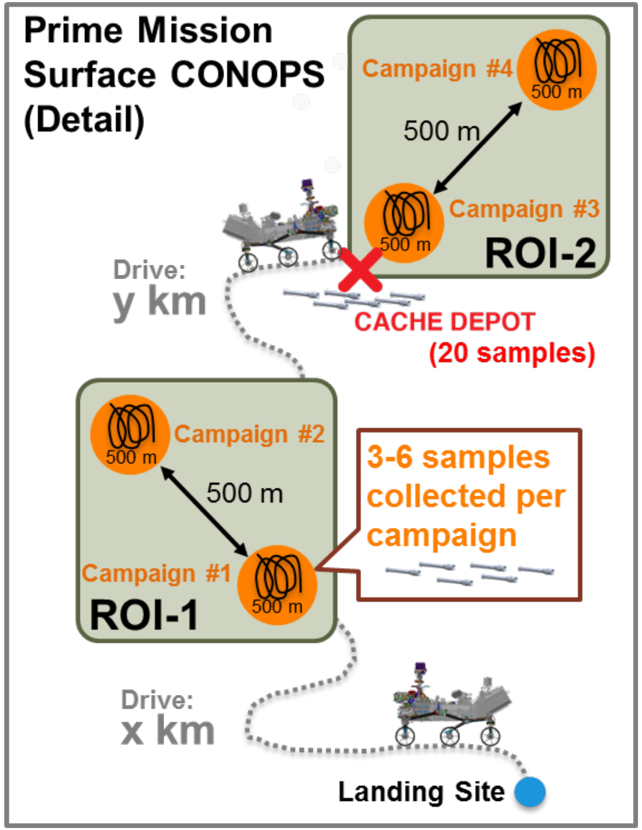
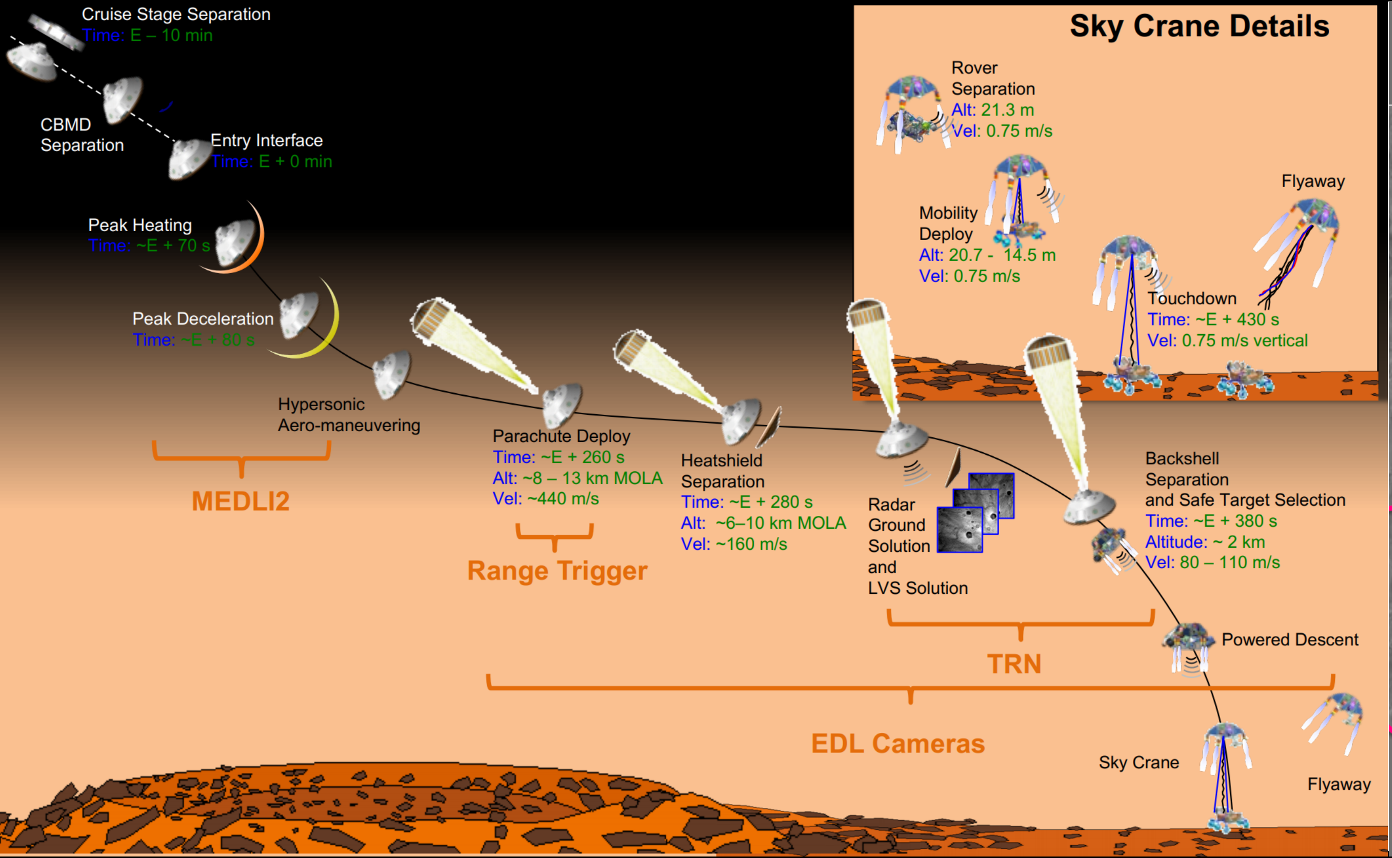
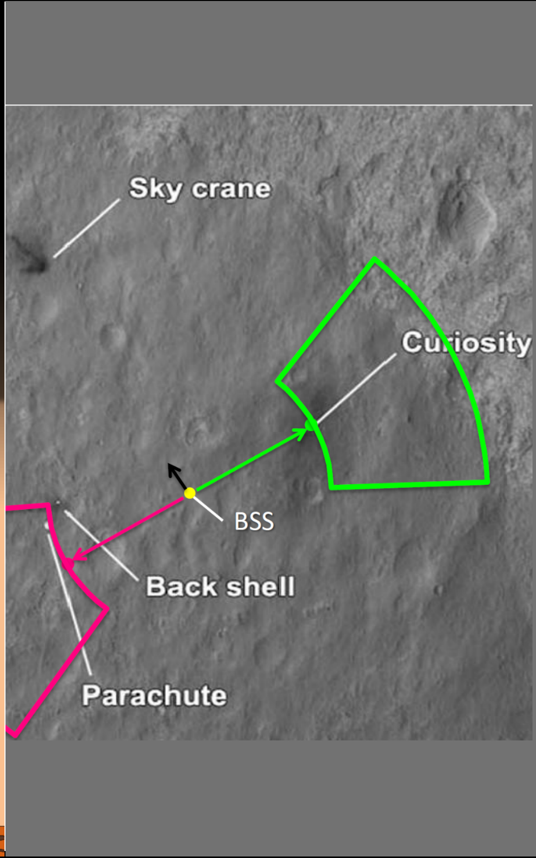
California Institute of Technology

- Explore an ancient environment that has the potential to have supported life in the past
- Assess the ability of this Martian environment to have preserved signs of past life (biosignatures) and search out potential evidence of these signs
- Gather a scientifically compelling and well-documented set of rock and soil samples and seal them in containers for potential return to Earth by a future NASA mission
- Demonstrate key technologies beneficial for future robotic and human exploration of Mars



MSL vs. Mars 2020 EDL Comparison

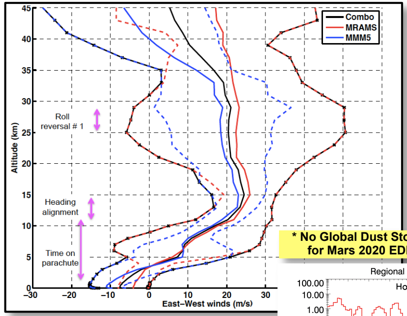




Atmosphere Characterization Progress (from LSW3)

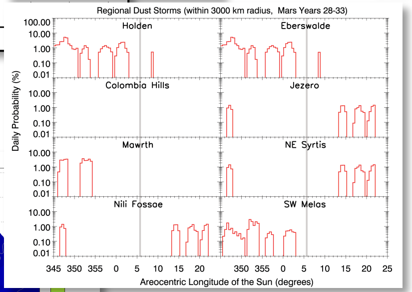
Jet Propulsion Laboratory
California Institute of Technology

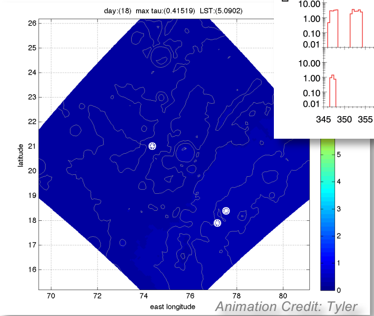
- Ran mesoscale models for new sites emerging from LSW2
  - Eberswalde
  - Columbia Hills
- Ran mesoscale dust storm scenarios for Syrtis region sites
  - Nili Fossae (ran through EDL simulations)
  - Jezero
  - North East Syrtis
- Generated dust storm statistics for Top 8 sites; very low likelihood of a dust event in 2020 landing season
- Delivered assessment of nominal atmosphere for LSW3 sites



* No Global Dust Storm observed for Mars 2020 EDL Season *

Credit: Cantor





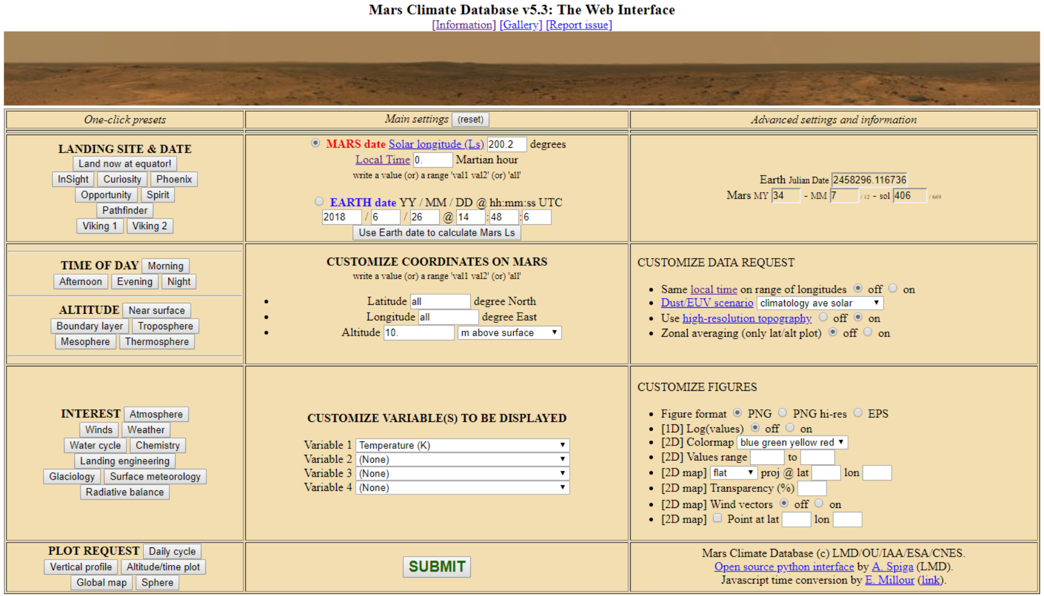
Animation Credit: Tyler

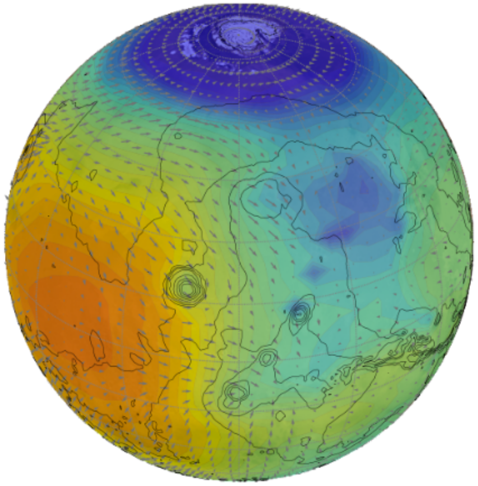
Current Mars 2020 CoA status is more mature than MSL at final site selection

Open Source Atmospheric Model: Mars Climate Database (MCD) v5.3

Jet Propulsion Laboratory
California Institute of Technology

- Developed at the Dynamic Meteorology Laboratory (LMD) at the Pierre and Marie Curie University, France – funded by ESA and CNES
- Accessible at: http://www-mars.lmd.jussieu.fr/mcd_python/
- A database of meteorological data derived from a General Circulation Model of the Martian atmosphere, and validated using available observational data





Example MCD Run: JEZ at Ls=180 at 50m AGL

Jet Propulsion Laboratory
California Institute of Technology

Ls

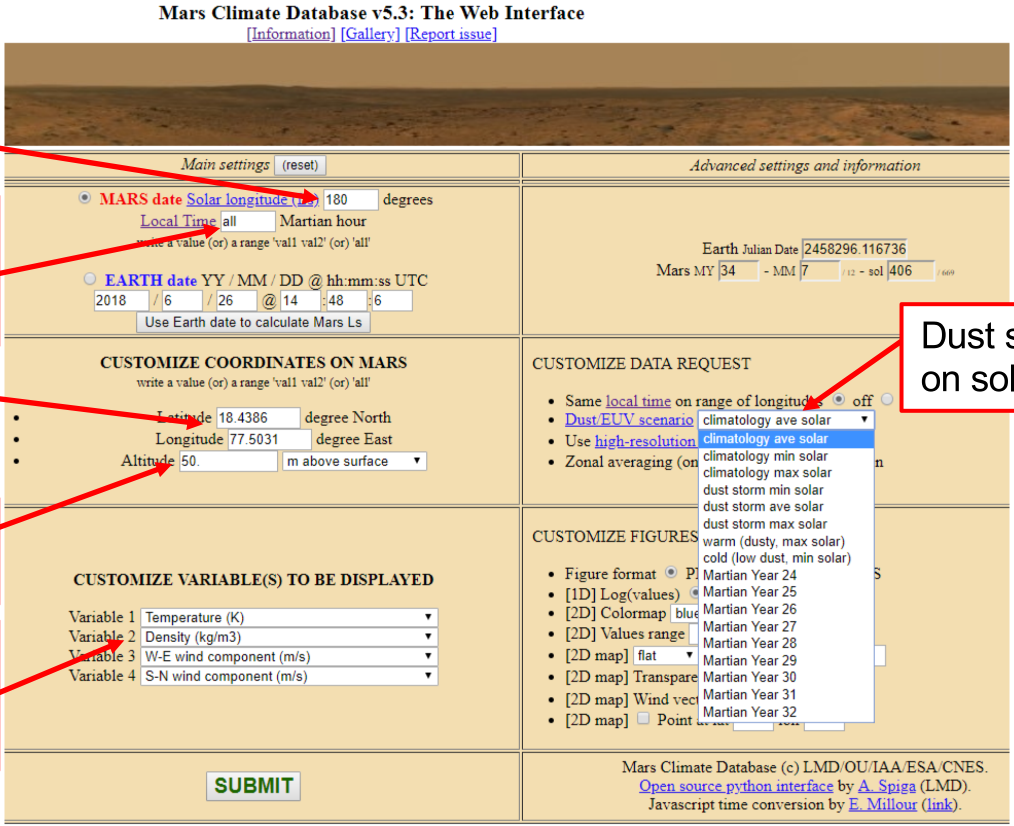
Retrieve data across Martian day

Landing Site lon/lat

Altitude above ground level (AGL)

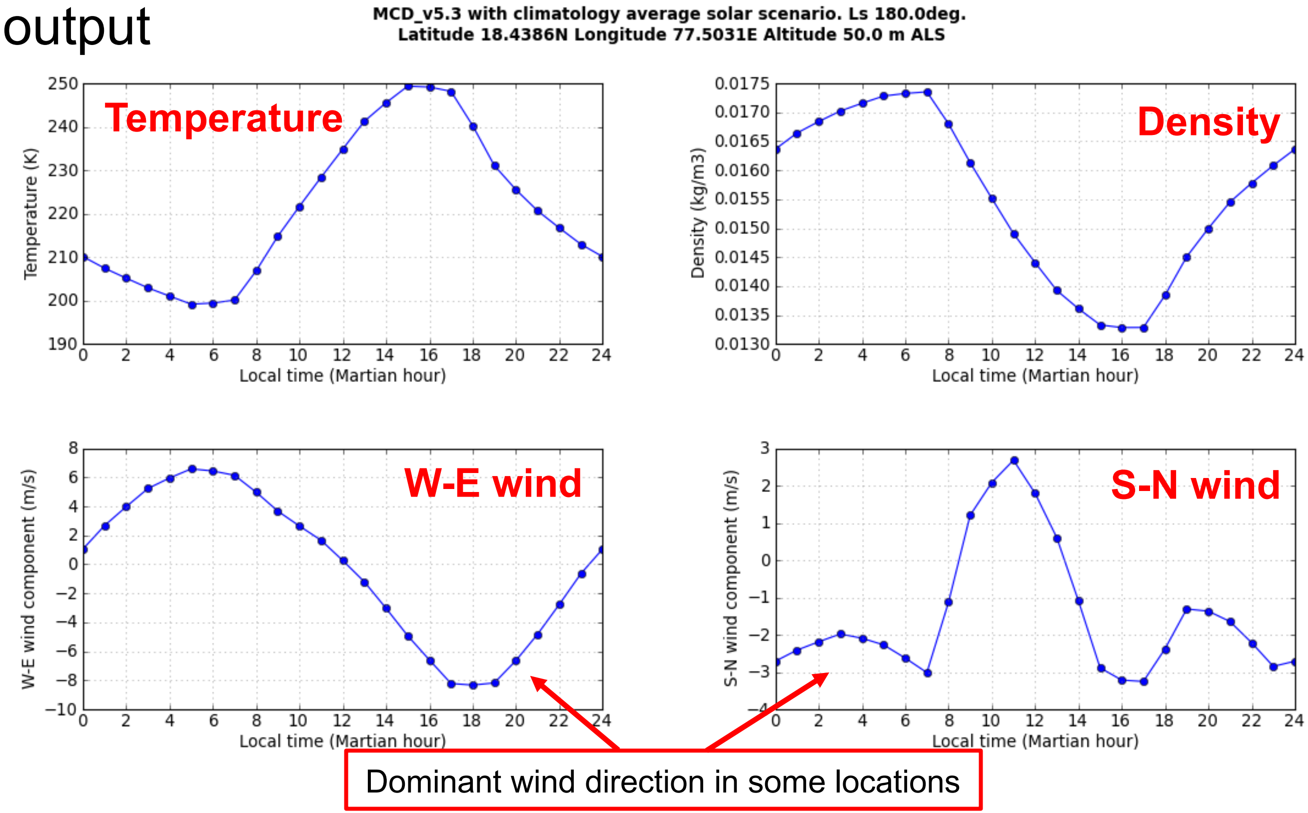
Variables to be extracted (4 at a time)

Dust setting based on solar activity



Example MCD Run: JEZ at Ls=180 at 50m AGL

- Example output



Landing Terrain Hazards Considered

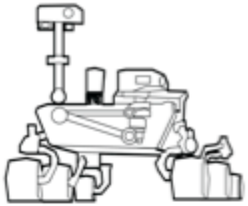
- Rocks
  - Large dangerous rocks identified through HiRISE imagery and smaller dangerous rocks estimated by analytical models
- High slopes
  - Identified through Digital Elevation Models of the environment
- Inescapable areas
  - Fresh craters with non-traversable boundaries
  - Sand ripples that look very challenging for traversal; identified through HiRISE imagery
- Thruster plume interaction
  - Bounding analysis for interaction risk with the thruster plume when landing on a given slope
- Relief over a 2.5km baseline
  - Topographical relief may require more fuel for a safe landing
  - A fuel budget constrains the amount of relief we can mitigate

MSL vs. Mars 2020 Surface Mission Comparison

Jet Propulsion Laboratory
California Institute of Technology

1.25 MARS YEARS
context

MSL



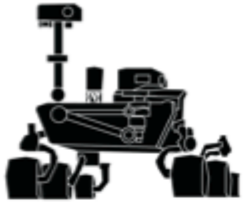
MARS YEARS:
1.25

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

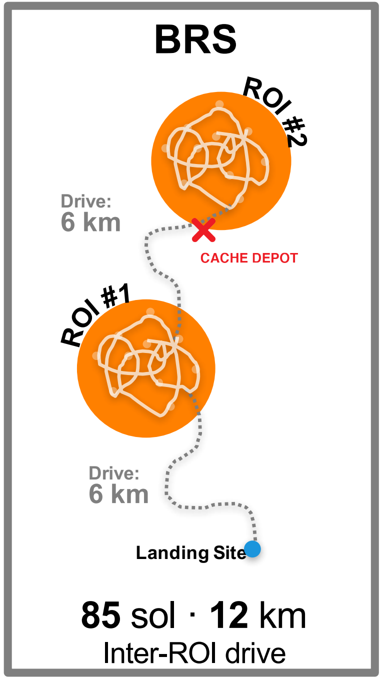
DISTANCE TO COVER:
15 km

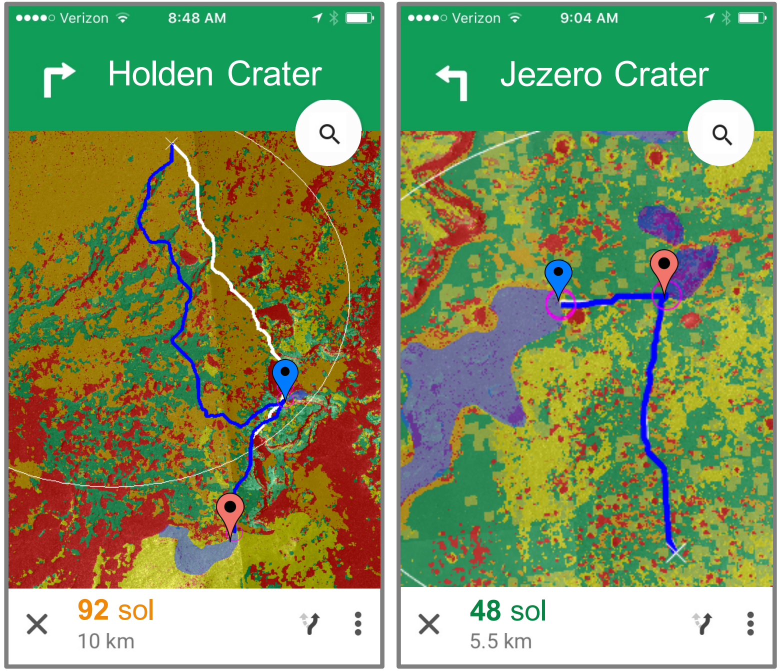
SAMPLES TO COLLECT:
20 drilled samples

Landing Site Specific Analysis

Jet Propulsion Laboratory
California Institute of Technology

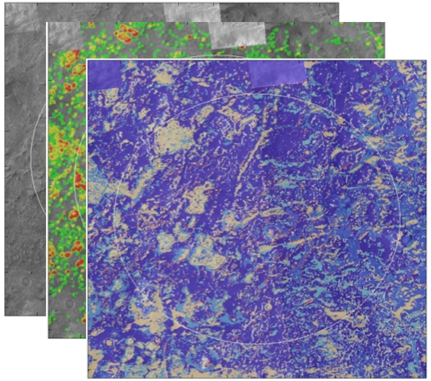
Attempting to move from a generic Baseline Reference Scenario (BRS) to analyzing a specific mission at each landing site



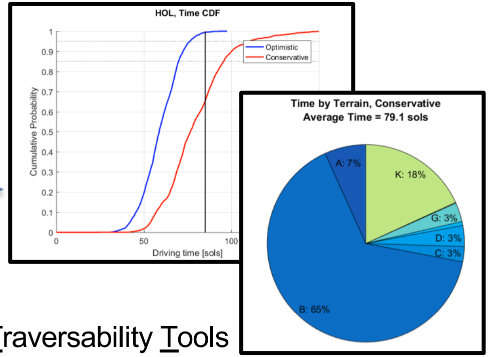


Data-driven Traversability Analysis

Inputs: slope, CFA, terrain type



Output: Statistics of time/distance



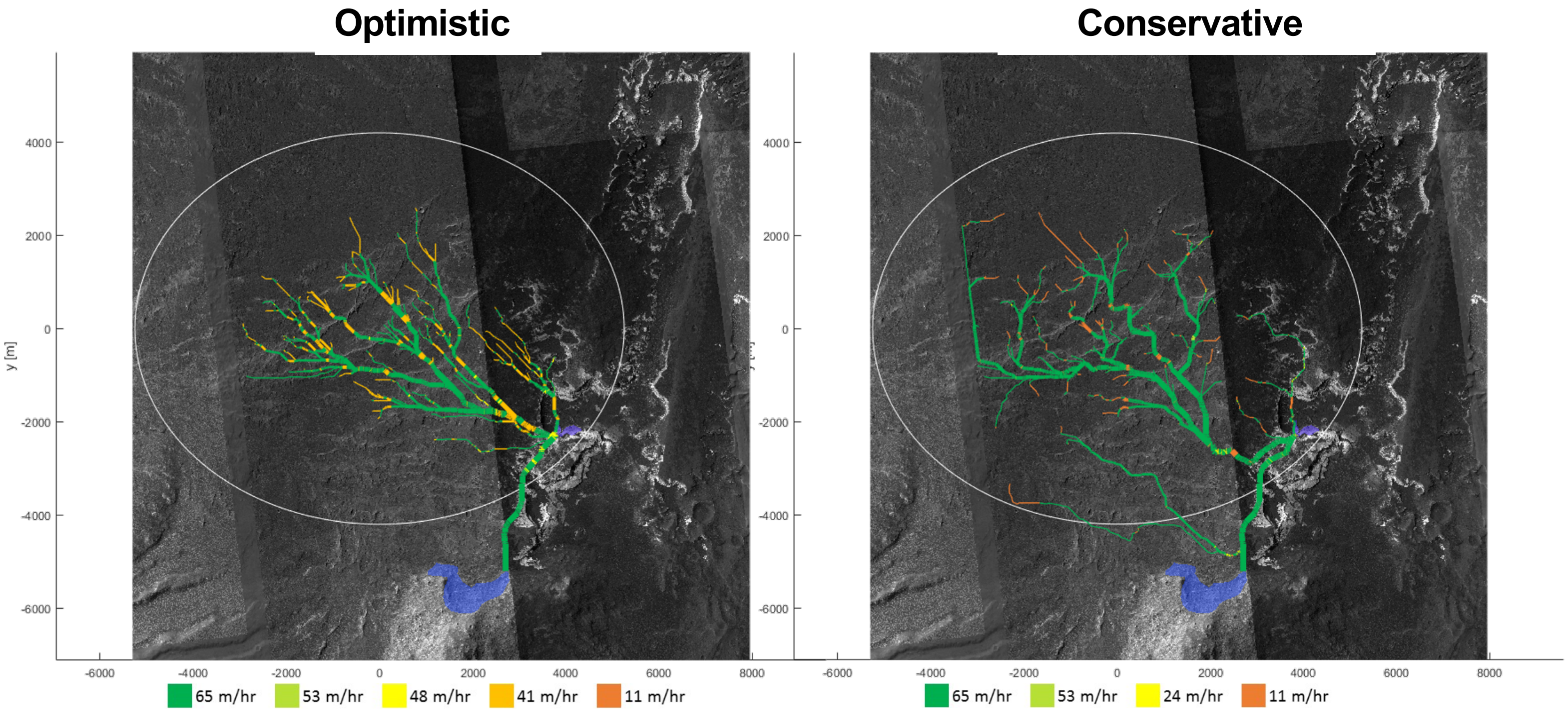
MTTT

MTTT = Mars Twenty-twenty Traversability Tools

- Uses slope, CFA, and terrain type to assess traversability (MSL did not use terrain classification)
- Outputs statistical distribution of driving time and distance to visit required ROIs
- Avoids subjectivity by algorithmic evaluation of terrain type and rock abundance
- Solves traveling salesman problem to find the minimum-time path to visit multiple ROIs (MSL had only one ROI)

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”



Summary of Traversability Assessment Results at LSW3

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California Institute of Technology

	90% Time [Sol]	90% Distance [km]	Traversability challenges
BRS	85	12	(Baseline reference scenario)
CLH	57.7 – 72.7	8.3 – 9.3	Go-to site
EBW	28.9 – 47.6	3.8 – 4.6	Mantling unit with ripples Scarps on delta
HOL	73.7 - 106.8	10.6 – 12.5	Go-to site; >60% covered by potentially no-Autonav ripples; highways exist but in unfavorable directions Access to ROI (layered deposit) challenging due to high slope/sand
JEZ	35.5 – 38.1	5.5 – 5.8	High CFA on SE of ellipse but ROIs are on NW
MAW	19.1 – 28.0	2.7 – 3.2	Surface roughness could limit the speed of Autonav, but can achieve mission with conservative estimate
NES	15.1 – 16.5	2.3 – 2.4	Buttes and sand deposits, but localized and easy to go around
NIL	66.7 – 86.7	9.9 – 10.6	Go-to site Ripples but mitigated by highway in the favorable direction
SWM	29.6 – 52.5	3.7 - 4.0	Scarps, but traversable routes seem to exist across

M2020 LSW3 Engineering Summary

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Site	EDL	Surface	Comments
Columbia Hills			
Eberswalde			
Holden			Likely to exceed the prime mission duration to accomplish science objectives
Jezero			
Mawrth			
NE Syrtis			
Nili Fossae			
SW Melas			Lack of confidence in atmosphere modeling results coupled with significant terrain hazards bordering the landing ellipse raise concerns

All candidate landing sites are viable; however, have some engineering concerns with Holden and SW Melas

Proposed Mars 2020 Surface Mission

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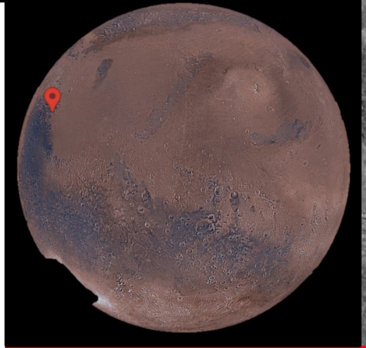

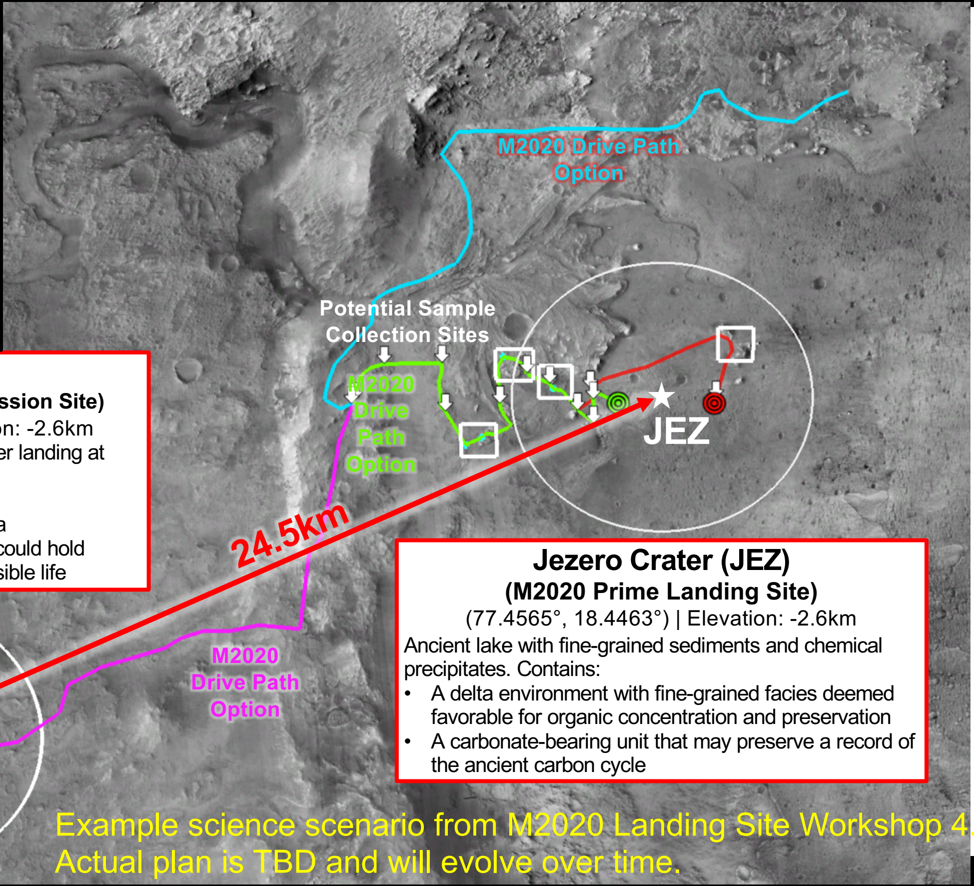

Midway (MDW)
(Proposed M2020 Extended Mission Site)
(77.0480°, 18.2747°) | Elevation: -2.6km
Extended mission option for M2020 after landing at JEZ. Contains:

- Highly diverse lithology
- Well-exposed blocks of megabreccia
- Phyllosilicates and carbonates that could hold evidence of past climate and of possible life

Jezero Crater (JEZ)
(M2020 Prime Landing Site)
(77.4565°, 18.4463°) | Elevation: -2.6km
Ancient lake with fine-grained sediments and chemical precipitates. Contains:

- A delta environment with fine-grained facies deemed favorable for organic concentration and preservation
- A carbonate-bearing unit that may preserve a record of the ancient carbon cycle

Example science scenario from M2020 Landing Site Workshop 4.
Actual plan is TBD and will evolve over time.

Mars 2020 Selected Landing Site – Jezero Crater

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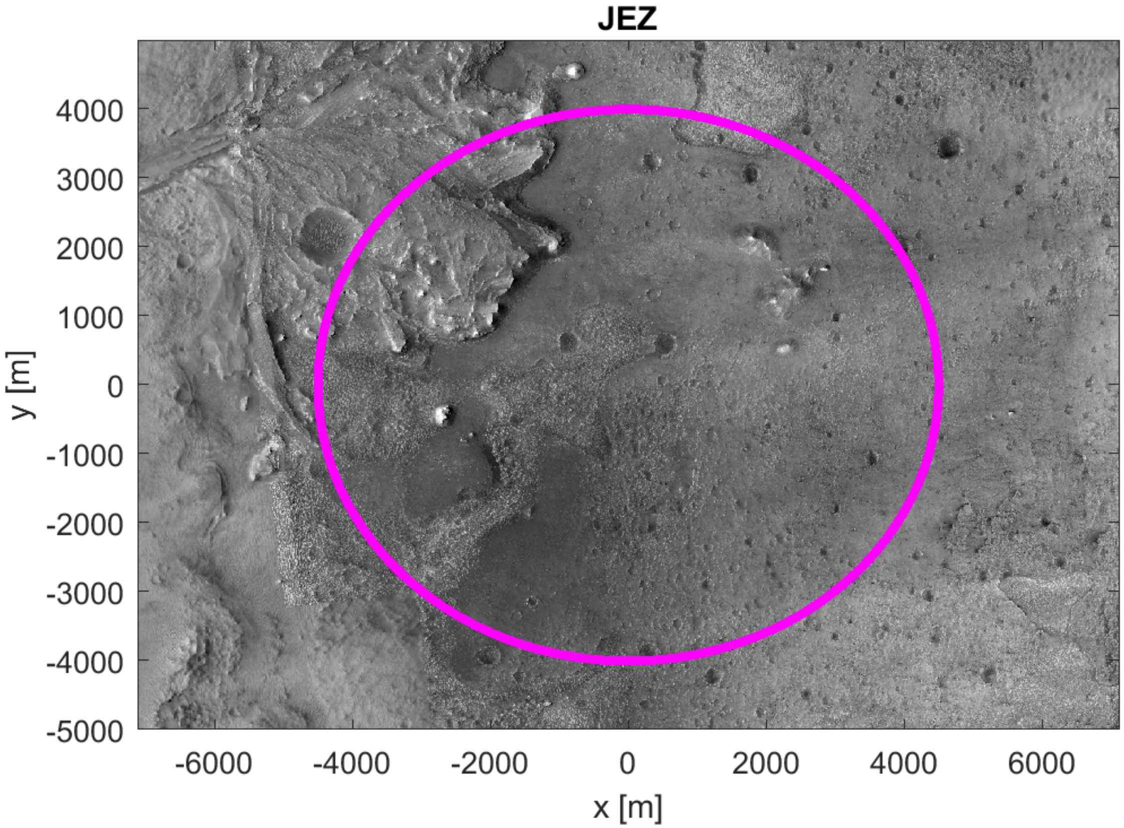
California Institute of Technology



Landing Site Selection for Human Missions

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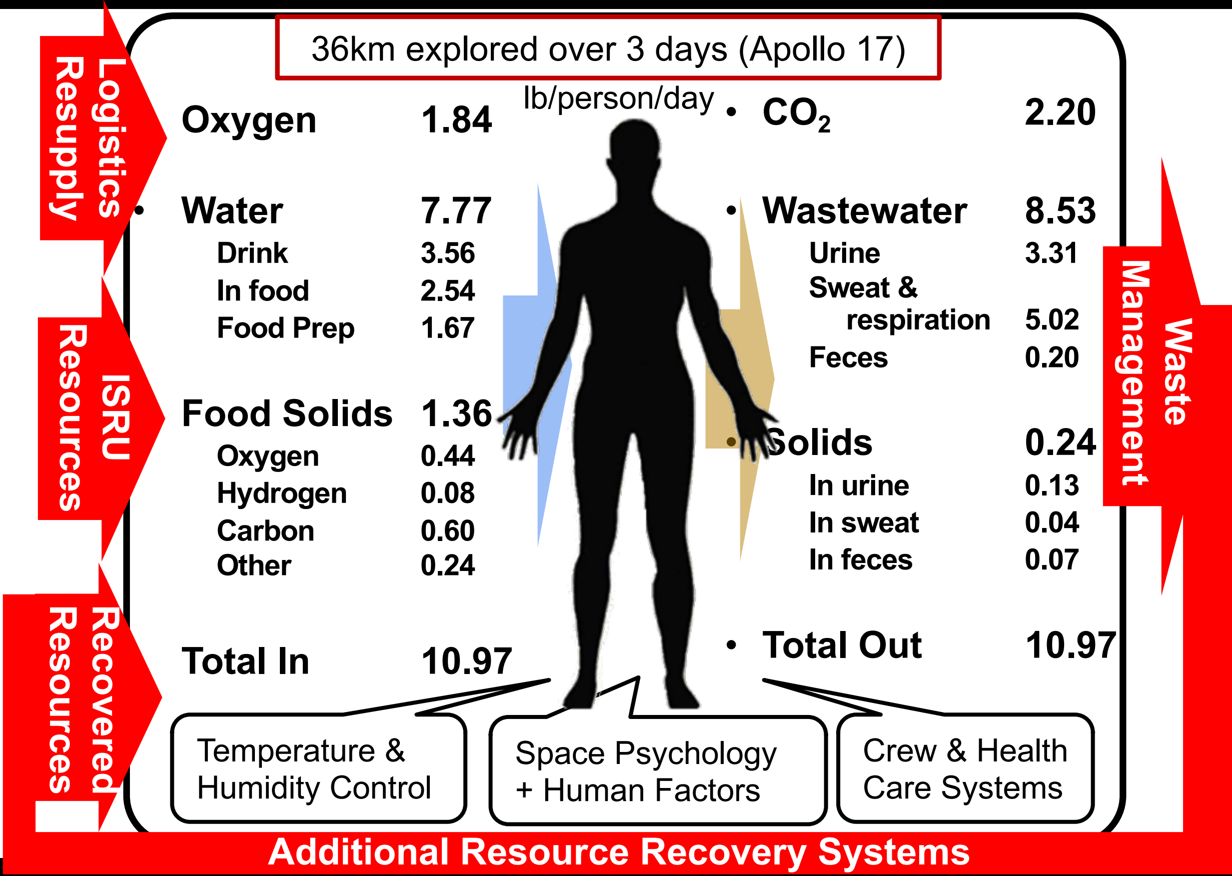
Robots vs Humans

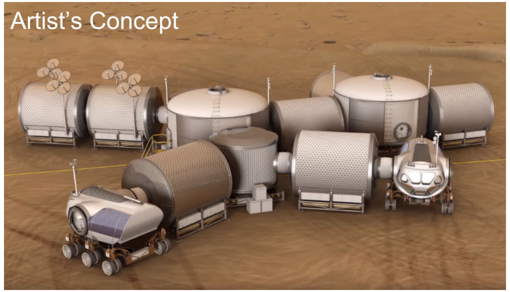
20.38km explored over 2424 days (MSL)

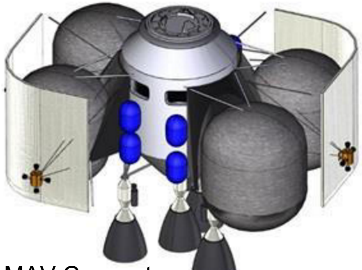
~1.8kWh/day power
~45kWh/day heat

*Average values listed

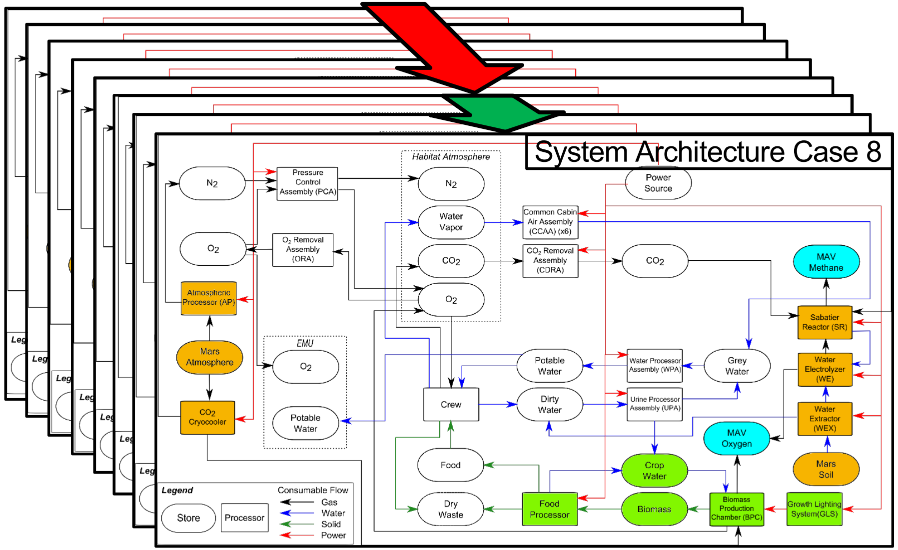


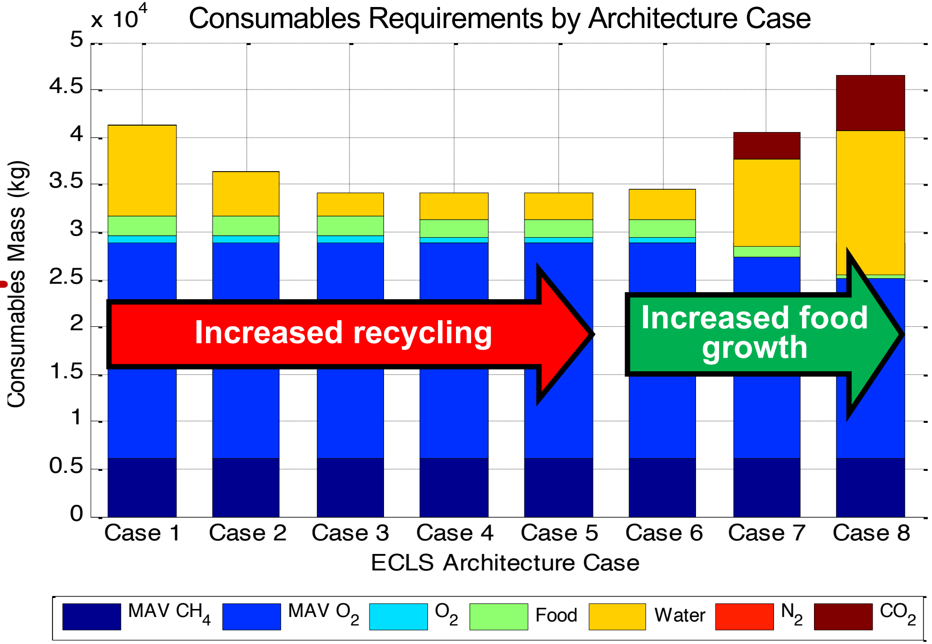
Estimating Combined Resource Demands (see Do PhD 2016 for details)





MAV Concept

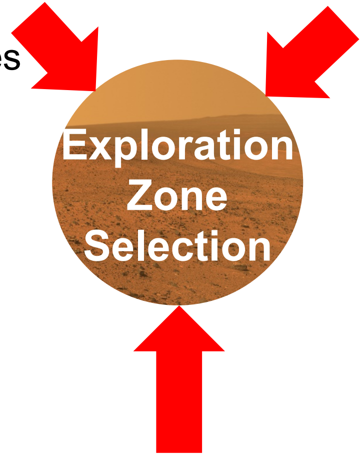




ISRU System Design
(for minimal mass, power, volume, complexity, maintenance, and spare parts demand; and maximum autonomy and reliability)

Landing Site Selection Activities for Human Mars Missions

- **Early 2015**: NASA HEOMD and SMD jointly begin activities to focus efforts on identifying requirements for human landing site selection (HLS2)
- **April 2015**: ISRU and Civil Engineering Working Group (ICE-WG) formed
  - Goal: identify resource abundance, quality, and accessibility requirements and data needs for informing HLS2. Identify capabilities that are key to establishing sustained human presence on Mars
- **April 2015**: Human Exploration Science Objectives Science Analysis Group (HSO-SAG) formed
  - Goal: define options and priorities for scientific objectives for human Mars mission campaigns. Define criteria that could be used to identify science sites of interest for future human exploration
- **June 2015**: Open call for landing site candidates released. Includes definition of an "Exploration Zone" – an area containing a landing site and regions of interest
- **October 2015**: NASA holds First Mars Human Landing Site/Exploration Zone Workshop. 47 Exploration Zone candidates proposed.



Exploration Zone – Working Definition

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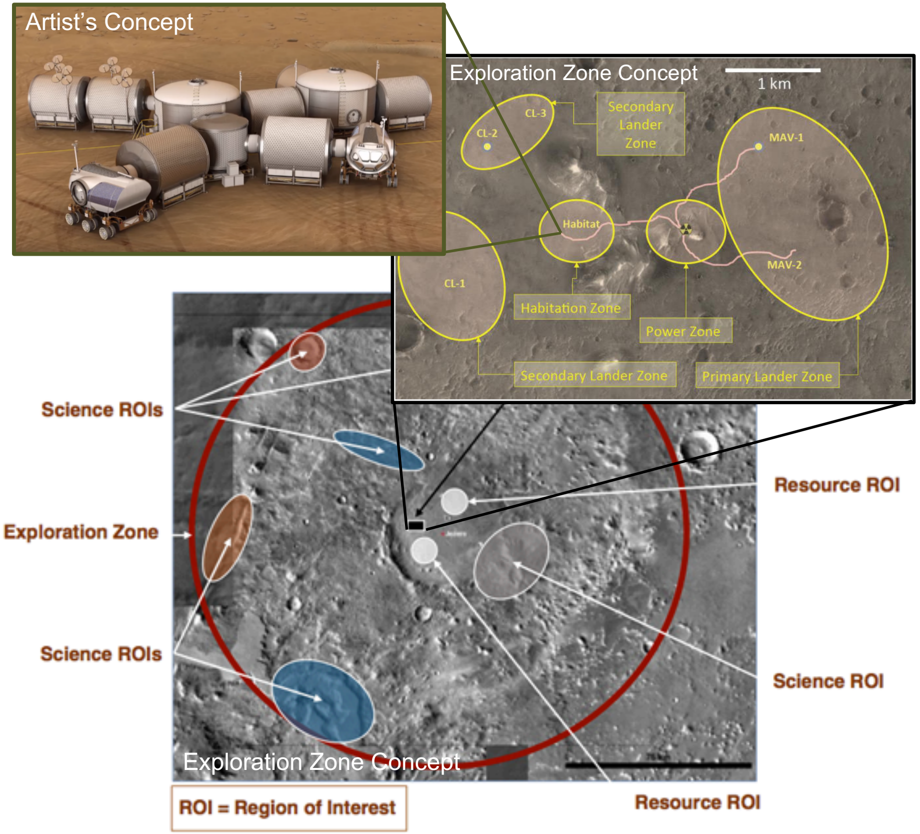
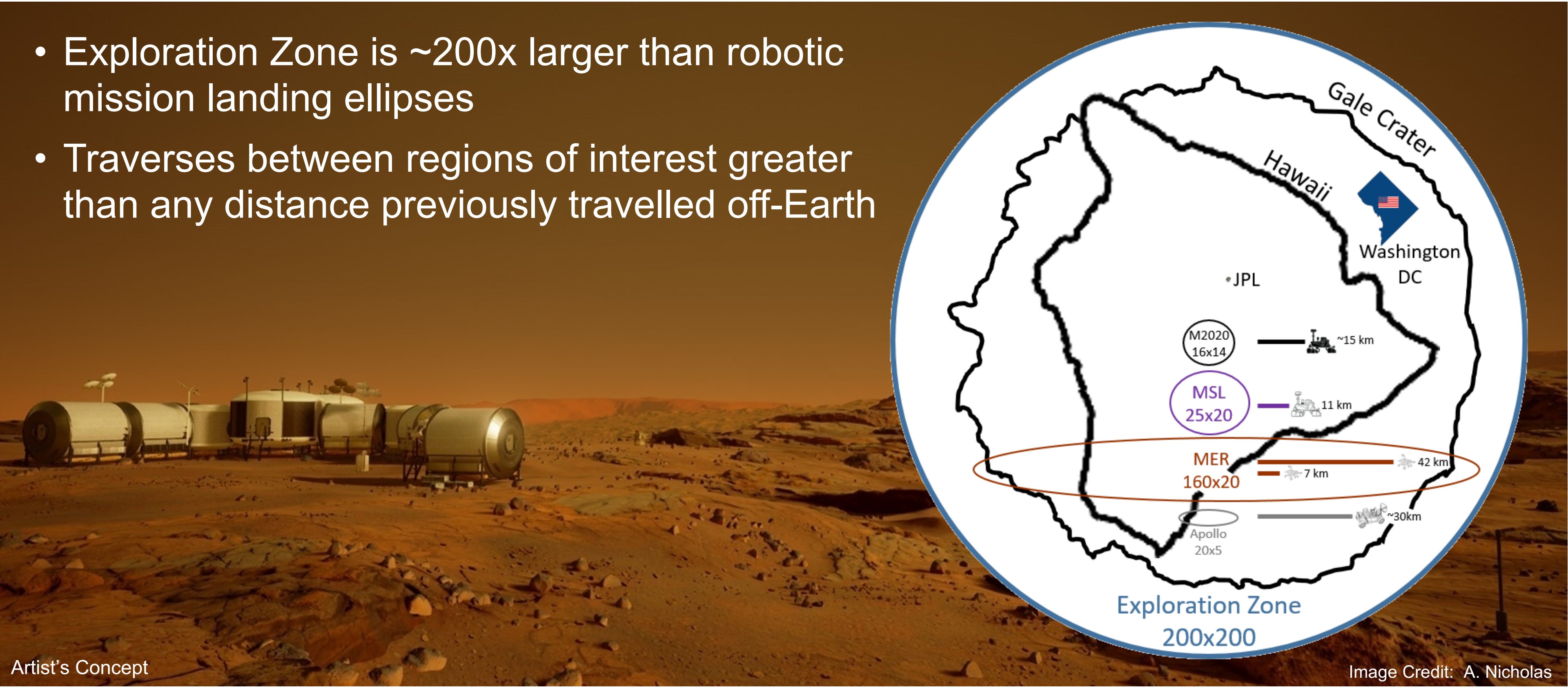
- 100km radius site at latitude band: ±50°
- Contains:
  - **Habitation Site**: Flat, stable terrain for emplacement of infrastructure, located ≤5km from landing site location
  - **Landing Site(s):** Flat, stable terrain, low rockiness, clear over length scales greater than landing ellipse
  - **Resource Regions of Interest**
    - One or more potential near-surface (≤3m) water resource feedstocks in a form that is minable by highly automated systems, and located within ~1-3km of ISRU processing and power infrastructure. Total extractable water should be ~100MT (supports ~5 missions)
    - Show potential for minable metal/silicon resources, mainly Fe, Al, and Si, located within ~1-2m of the surface
  - **Science Regions of Interest**
    - Related to Astrobiology, Atmospheric Science, and Geoscience



Exploration Zone in context

- Exploration Zone is ~200x larger than robotic mission landing ellipses
- Traverses between regions of interest greater than any distance previously travelled off-Earth



Artist's Concept

Image Credit: A. Nicholas

Exploration Zone Video

https://www.youtube.com/watch?v=94bIW7e1Otg

47 Exploration Zone Candidates

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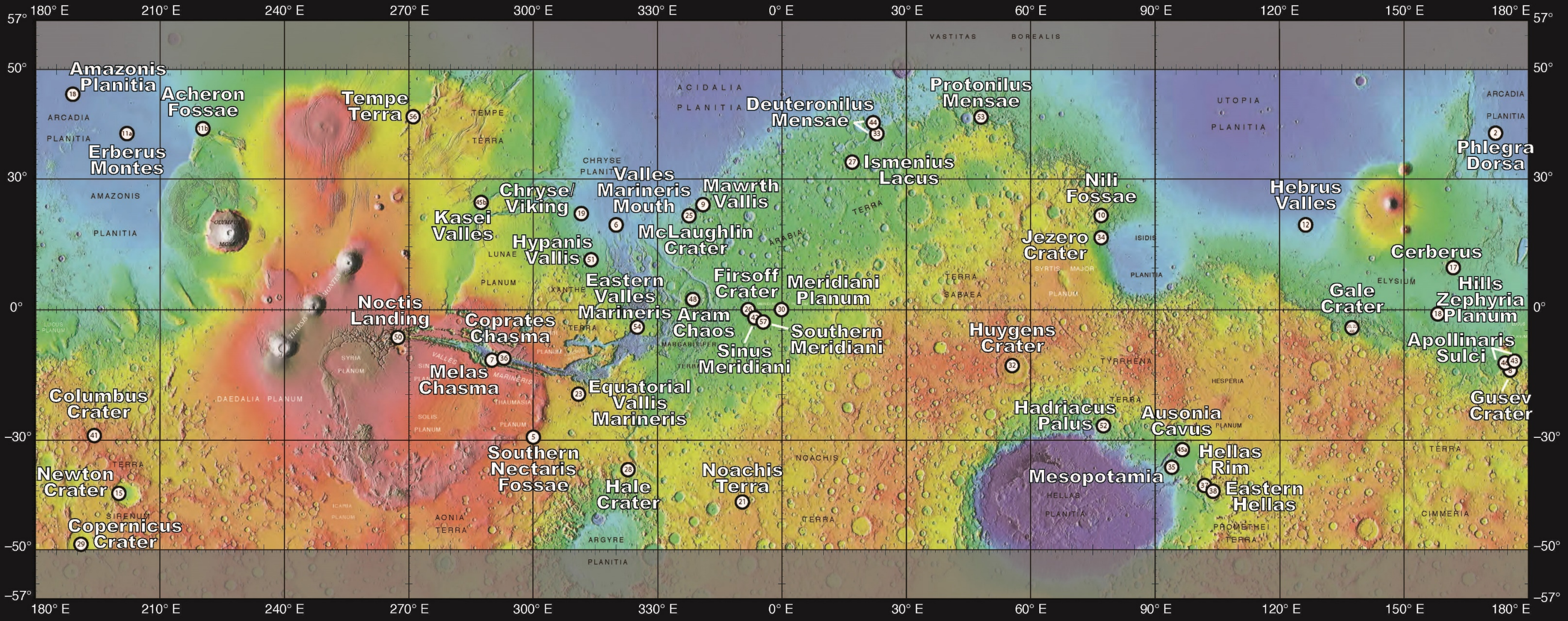
California Institute of Technology



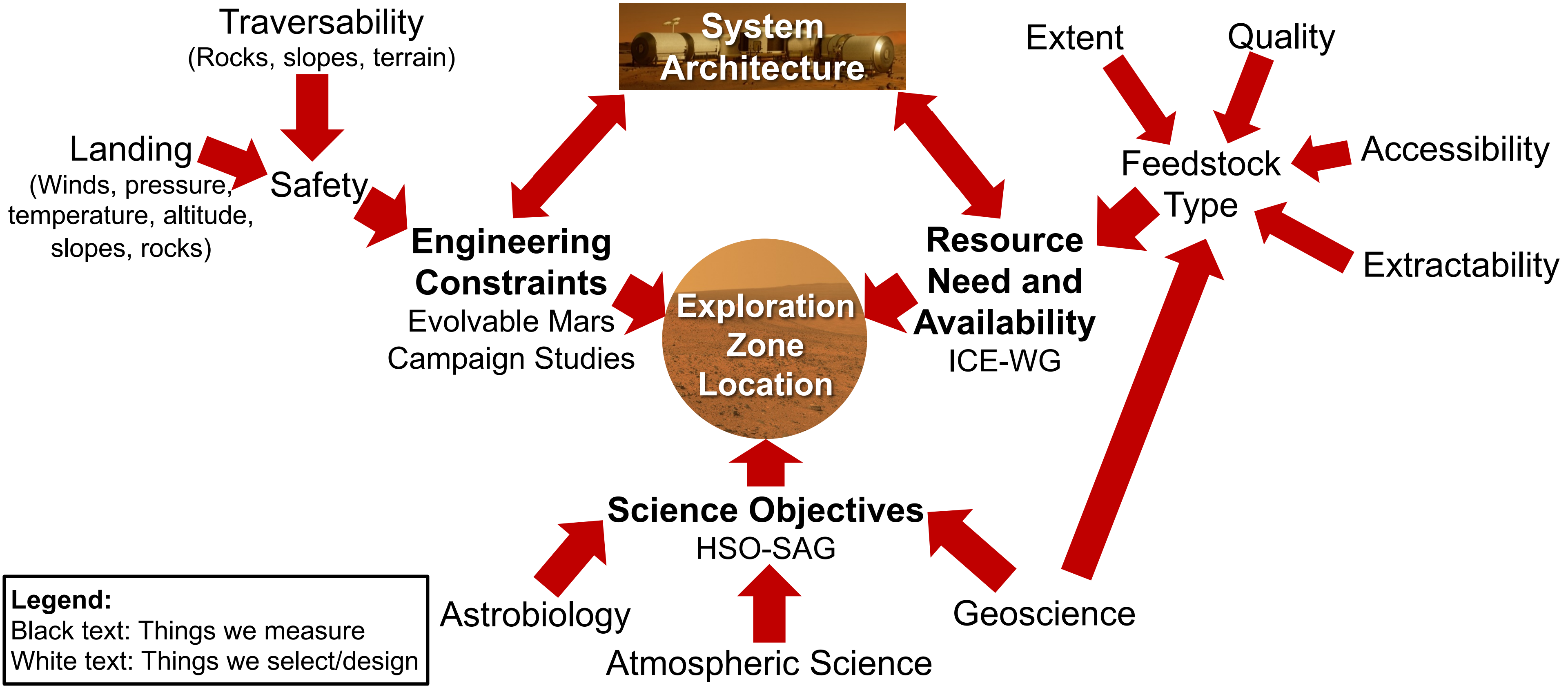
Exploration Zones proposed for humans to Mars.
00 Numbers correspond to the abstract submission #
At the equator, circles are ~100km radius

version 12 October 16, 2015

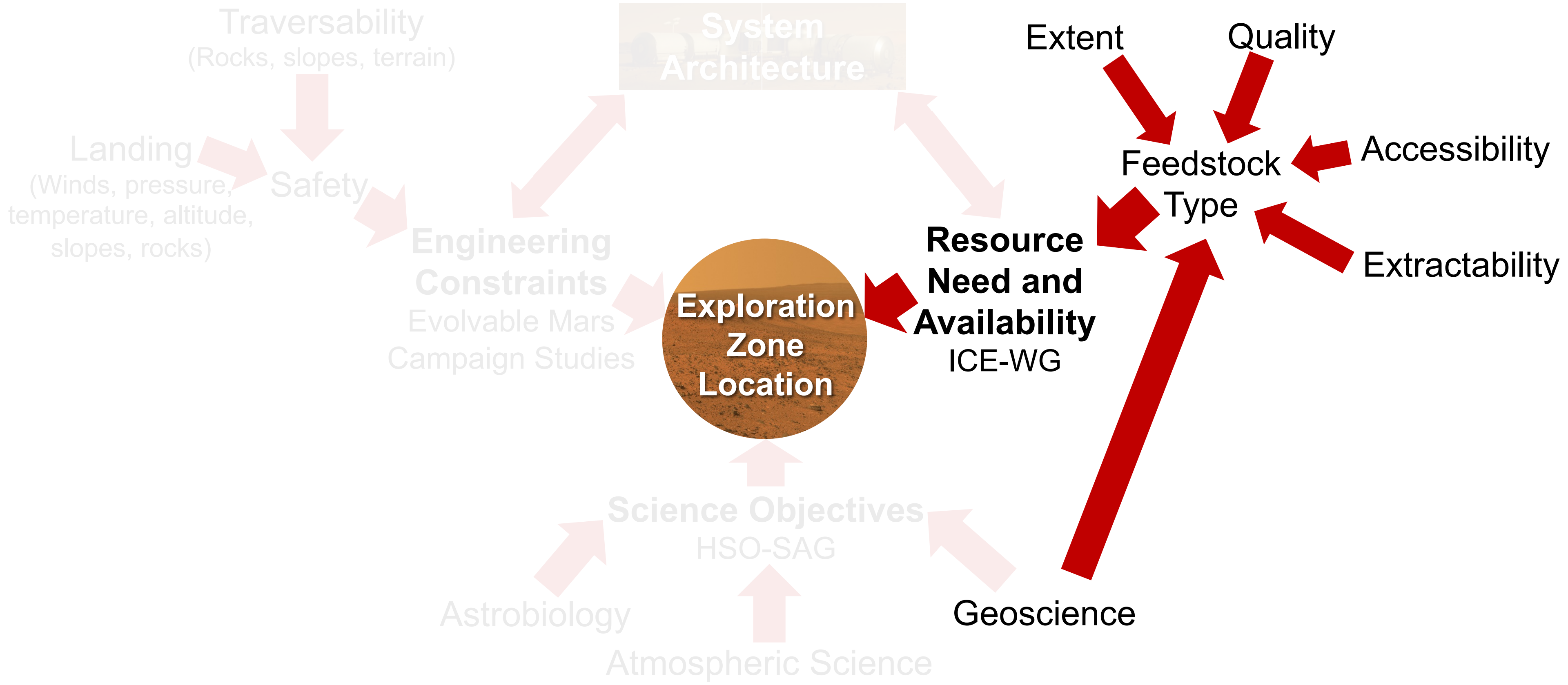
Prepared By: Lindsay Hays, Mars Program Office
lhays@jpl.nasa.gov

(A Subset of) the Human Landing Site Selection Tradespace

Jet Propulsion Laboratory
California Institute of Technology



Unique to Human Exploration



Overview of Follow-On Studies

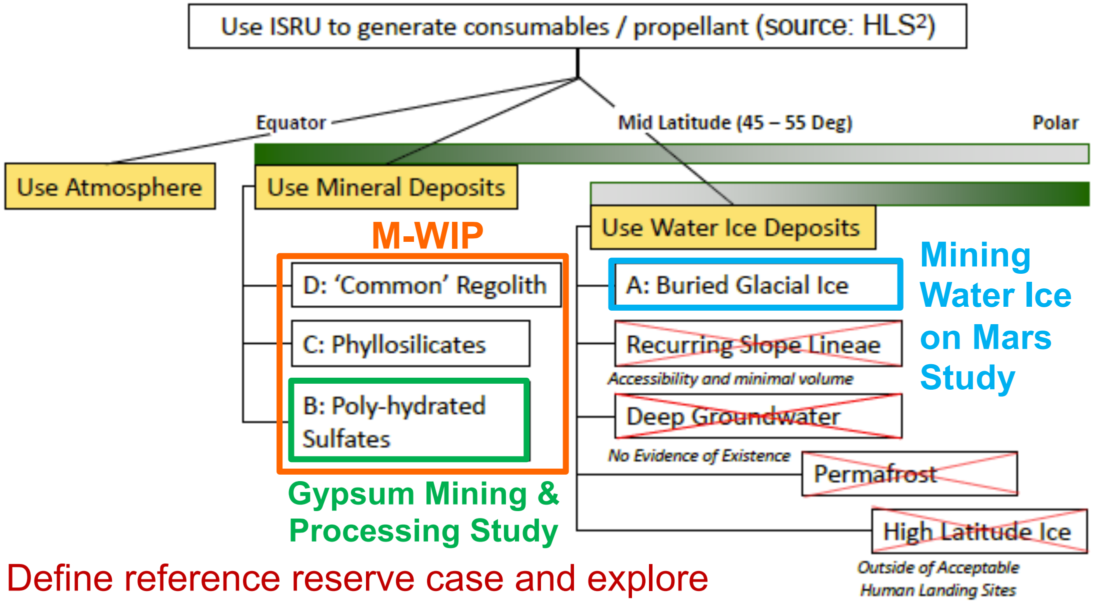
1. M-WIP Study
2. Mining Water Ice Study
3. AGU Workshop
4. Gypsum Study
5. Mars Water Mapping

Workshop Results:

- Imaging requests for HiRISE and CRISM instruments on MRO collected. Imaging currently underway
- Defined four most common types of water resource deposits for further exploration

NASA Sponsored Activities Since:

Jan–April 2016:	Mars Water ISRU Planning (M-WIP Study)
April–July 2016:	Mining Water Ice on Mars Study
Dec 2016:	AGU Mars Water Exploration Workshop
June–Aug 2017:	Gypsum Mining and Processing Study
June 2017–Oct 2018:	Mars Water Mapping Project

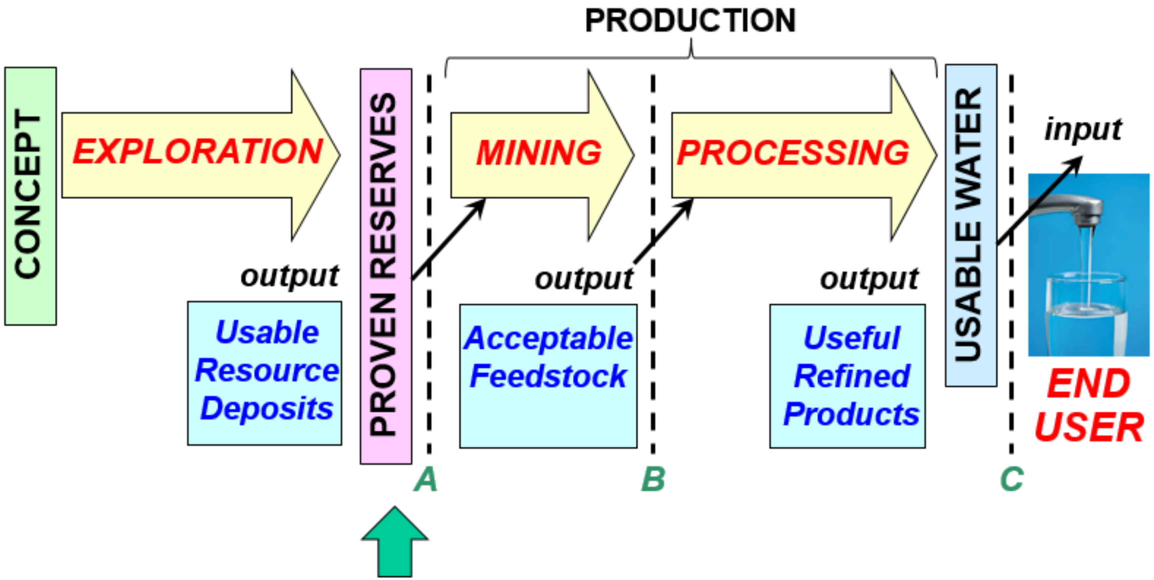


Define reference reserve case and explore feedstock mining and processing techniques

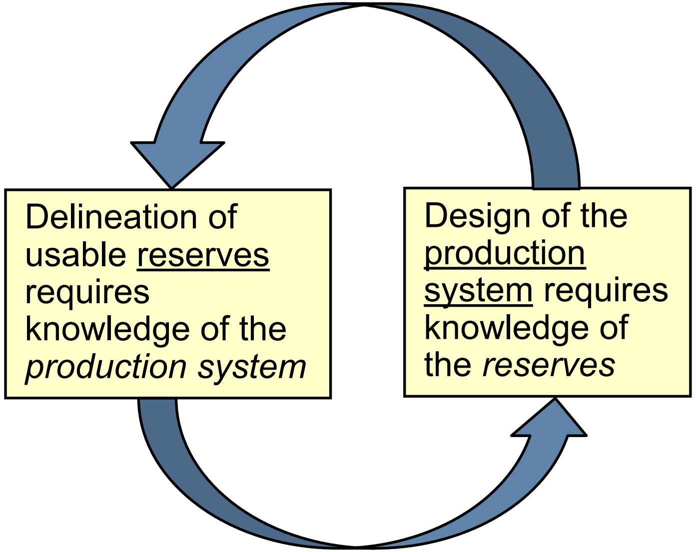
Better understand current distribution of water on Mars and the form in which it exists

Image Source: P. van Susante, M-WIP (2016)

M-WIP Study Overview



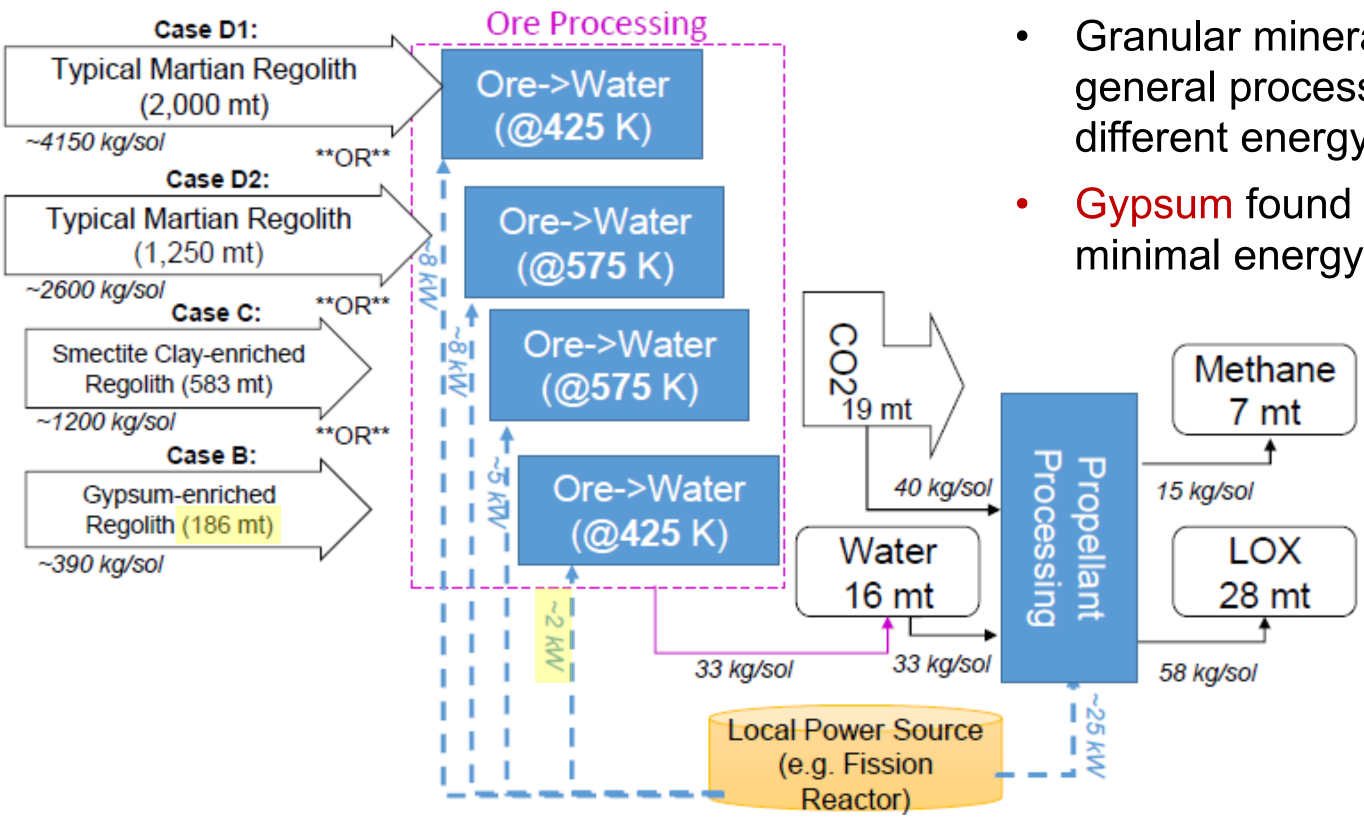
"Reserves" are the essential interface between "exploration" and "production"



Because of this coupled relationship, both exploration and engineering need to advance together.

Source: M-WIP (2016)

M-WIP Study Results Overview



- Granular mineral deposits share same general processing strategy but have different energy implications
- Gypsum found to be the minimal mass, minimal energy feedstock

Source: M-WIP (2016)

M-WIP Study Results Overview

The ranked value of information for assessing potential for engineering viability

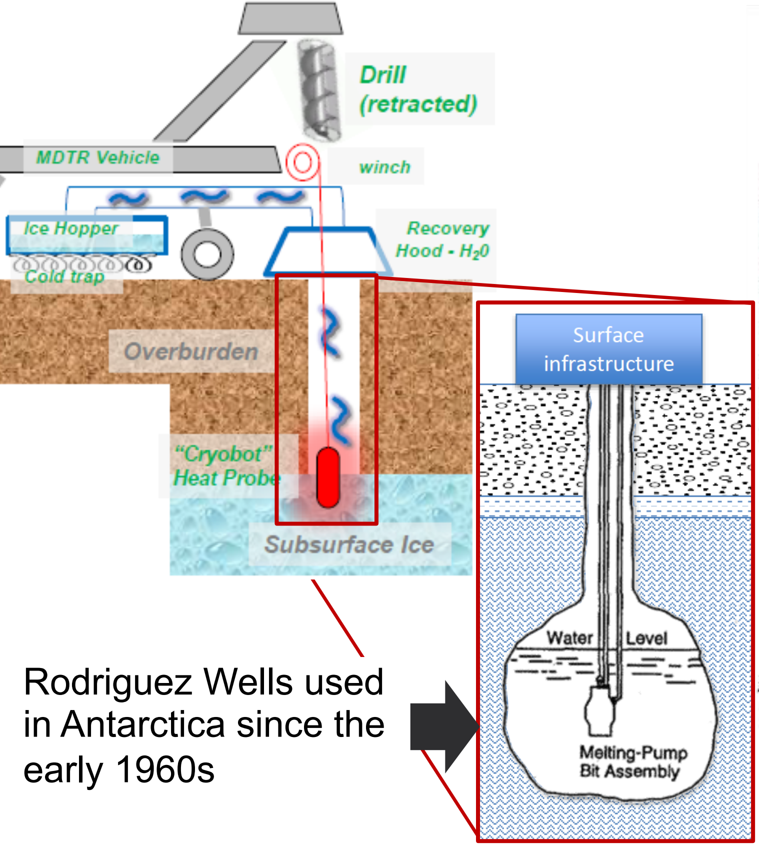
CASE	#1	#2	#3
A1 (Ice+open pit)	Thickness of overburden	Mechanical properties of overburden	Mechanical consistency of ore deposit
A2 (Ice+subsurface)	Mechanical consistency of ore deposit	*Thickness of overburden*	*Mechanical properties of overburden*
B (hydrated sulfate)	2D geometry/size of ore deposit	Mechanical consistency of ore deposit	Distance to processing plant
C (clay)	2D geometry/size of ore deposit	Mechanical consistency of ore deposit	Distance to processing plant
D (regolith)	Water concentration of ore deposit	Mechanical consistency of ore deposit	Chemical properties of ore deposit

Information in cells shaded in blue are those for which **preliminary assessments can be made from orbit**, those in green **require data collected in situ**. For Case A2 only parameter #1 was ranked high priority, parameters #2 and #3 (in italics) were ranked medium priority.

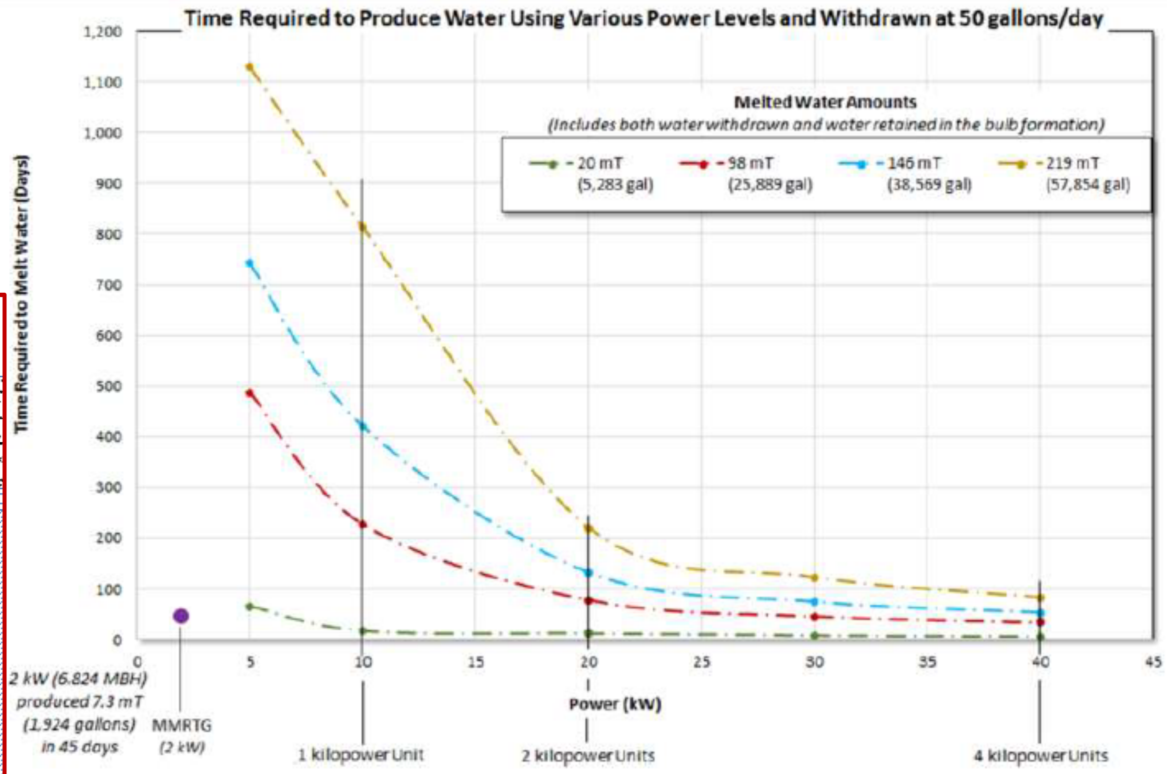
Source: M-WIP (2016)

Mars Water Ice Mining Study Results Overview

1. M-WIP Study
2. **Mining Water Ice Study**
3. AGU Workshop
4. Gypsum Study
5. Mars Water Mapping



Rodriguez Wells used in Antarctica since the early 1960s



Note: assumes -80° C ice

Source: Mars Water Ice Mining Study (2016)

Gypsum Mining and Processing Study Overview

M-WIP found that gypsum was the most attractive mineral feedstock

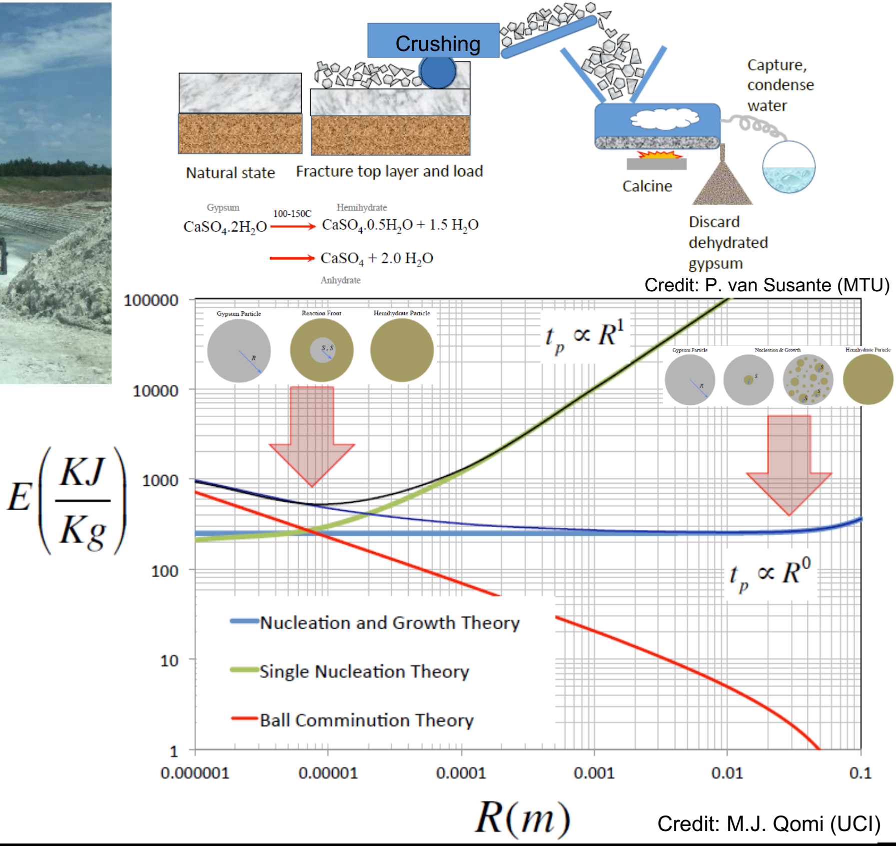
- However, M-WIP assumed granular materials
- Better understanding of processing bulk gypsum needed

This study:

- Explored gypsum mining and crushing approaches on Earth and suggested concepts for integrated gypsum processing systems on Mars
- Estimated optimal target grain sizes for minimal energy crushing and water extraction from gypsum

Forward Work by MTU:

- Mars-based gypsum mining & processing concepts developed. Plans underway for prototype development



Mars Water Mapping Projects

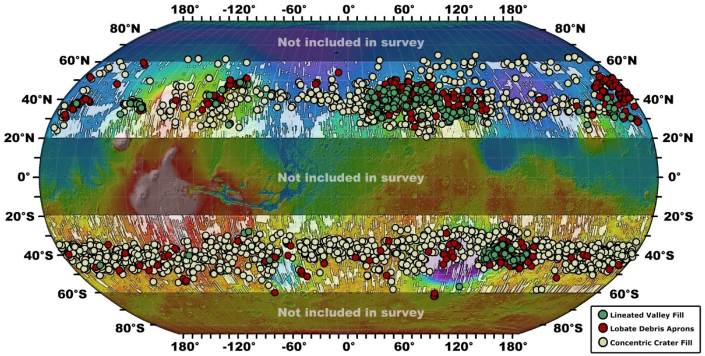
AGU Water Exploration Workshop (Dec 2016)

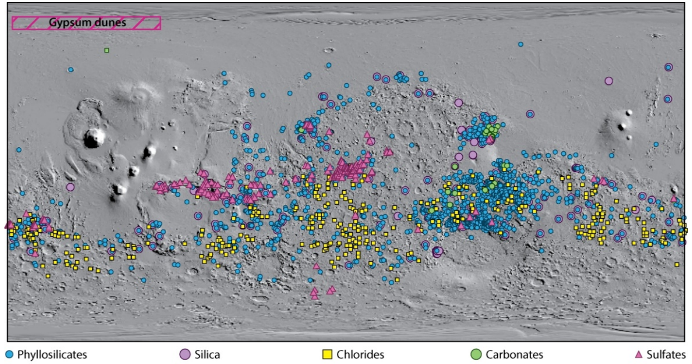
- Invited members of the Mars science community to discuss options for combining existing raw orbital datasets in a way that would help to identify sites or regions with high potential for productive water deposits
- Six candidate data products developed in real time. Top two selected for further development → RFP developed

Mars Water Mapping Projects (Ongoing)

- RFP Released June 2017. Requested proposals for two tasks:
  - **Task A – Subsurface Ice Mapping** (Arcadia Planitia Proof of Concept)
    - *Within a single 5-10° wide longitudinal swath from 0°-60°N latitude, generate a map that identifies potential locations of subsurface water ice at low- to mid-latitudes and characterizes the nature of the gradational boundary from regions of continuous ice to discontinuous ice, through to regions of no ice.*
  - **Task B – Hydrated Minerals (Global Map)**
    - *Develop algorithms to partially automate the processing of spectra of hydrated mineral detections. Use developed algorithms to generate global map of all existing near-surface hydrated mineral detections*
- Projects currently underway. Maps expected May 2019

Source: M-WIP (2016)





Source: M-WIP (2016)

Mapping Water on Mars

Pre-decisional Information – For Planning and Discussion Purposes Only

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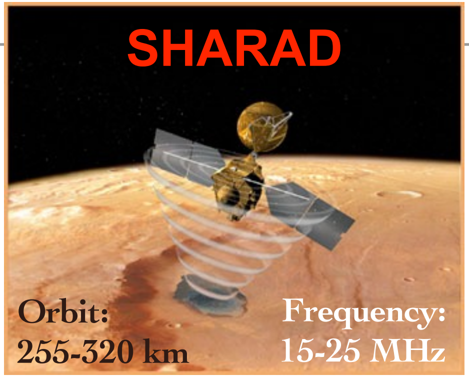
California Institute of Technology

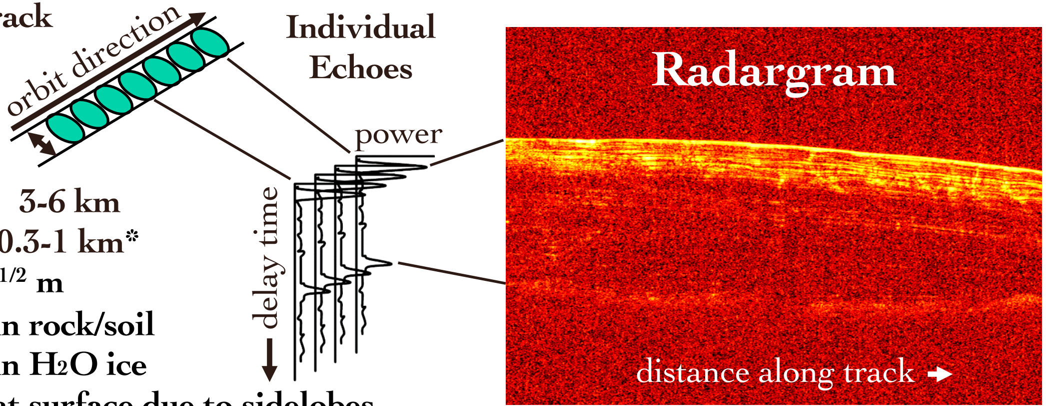
MRO's Shallow Radar sounder



Primary Objective

Map subsurface dielectric interfaces and interpret them in terms of the occurrence and distribution of expected materials, including rock, regolith, water, and ice.

Ground Track



Resolution

Cross-track: 3-6 km

Along-track: 0.3-1 km*

Range: 15 $\varepsilon_r^{-1/2}$ m

≈ 6 m in rock/soil

≈ 8 m in H_2O ice

≈ 20 m at surface due to sidelobes

* Along-track resolution is improved using synthetic aperture radar (SAR) processing techniques

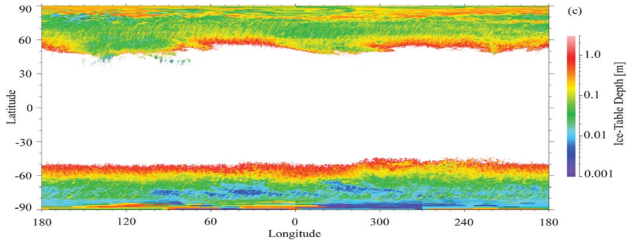
Slide credit: Than Putzig (PSI)

Slide credit: Than Putzig (PSI)

Prior detection of shallow (<1 m) water ice

- Theory since the 1960s and thermal measures since the 1990s indicate that ice is likely present across high (>50°) latitudes of Mars.

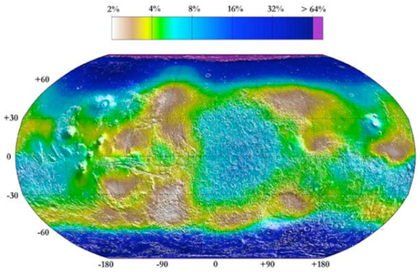
Thermal data



TES derived Depth of the ice table [Mellon et al., 2004].

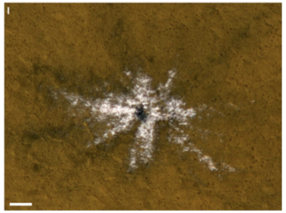
- In the early 2000s, the Mars Odyssey Neutron Spectrometer found clear indications of hydrogen in the form of water ice in these same regions.

Neutron data



Water-equivalent hydrogen content of the semi-infinite layer of water-bearing soils [Feldman et al., 2004].

- Fresh ice-exposing small impact craters reveal high concentrations within the upper 1m, sometimes at lower latitudes.

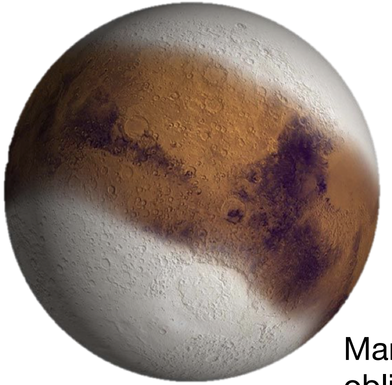


HiRISE image of fresh crater with icy ejecta [Byrne et al., 2009; Dundas et al., 2013]

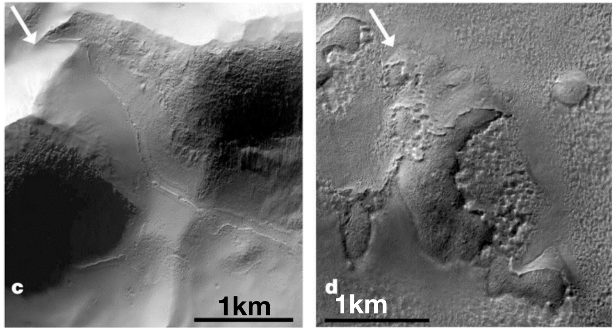
Slide credit: Than Putzig (PSI)

Morphologic indicators of water ice, shallow & deep

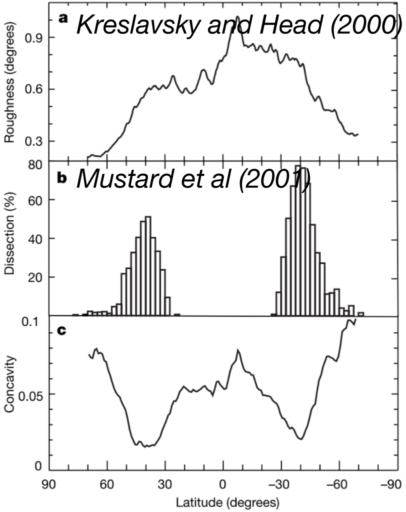
- Combination of high resolution image (MOC) and surface roughness studies (MOLA) led to the Mars Ice Age Hypothesis (Head et al., 2003).



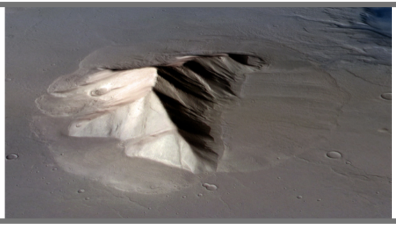
Mars at low obliquity?



Dissected Mantle at mid-latitudes



- Large scale lobate features exhibiting evidence of flow within the mid latitudes and along the flacks of tropical volcanoes have been interpreted to be glacial in origin

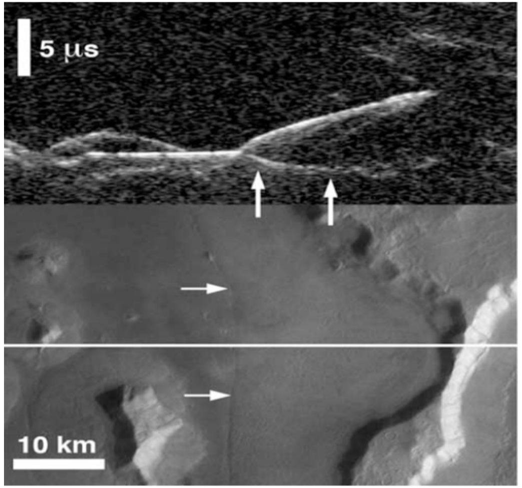


Promethei Terra region (HRSC Data)

Slide credit: Than Putzig (PSI)

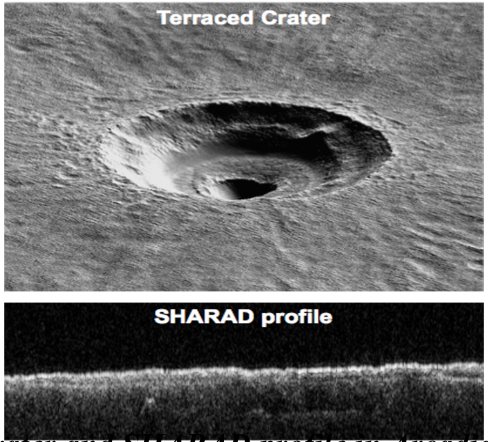
Prior detection of deep (>20 m) water ice

From 2008, MRO Shallow Radar (SHARAD) has shown that some of the glacial features are nearly pure water ice.



SHARAD profile and HRSC image along radar ground track over debris-covered glacier in Deuteronilus [Plaut et al., 2009].

From 2014, SHARAD detection of mid-latitude non-glacial ices—at Phoenix and further south in Arcadia and Utopia Planitiae—have been reported.



Terraced crater and SHARAD profile in Arcadia Planitia. Shallow subsurface reflector in profile corresponds to lower crater terrace at ~40 m depth. This yields subsurface material properties indicative of ground ice [Bramson et al., 2015].

SWIM Approach to Mapping Ice

1. Prior State of Knowledge
2. Methods
3. Arcadia Planitia Results
4. Expanded Study Plans

- Previous Martian subsurface ice studies used datasets in **isolation** or combined techniques in **limited geographical areas.**

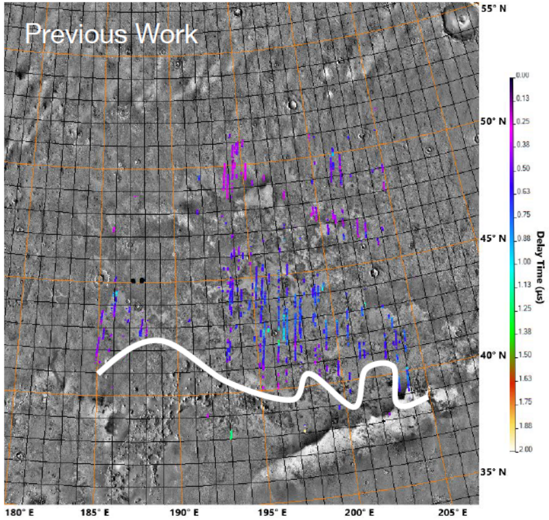
- For this study, we ***combine previous methods with newly developed techniques*** to probe the subsurface for water ice. New techniques include:
  - Measuring ***SHARAD surface power return*** to infer presence of ice within the top 5 m.
  - State-of-the-art ***super-resolution processing techniques*** that increase data resolution, potentially resolving top of ice.
  - The ***"split-chirp" technique***, sub-band processing to measure ***material loss properties*** - thereby constraining bulk composition.

Slide credit: Than Putzig (PSI)

SHARAD Subsurface Reflector Mapping

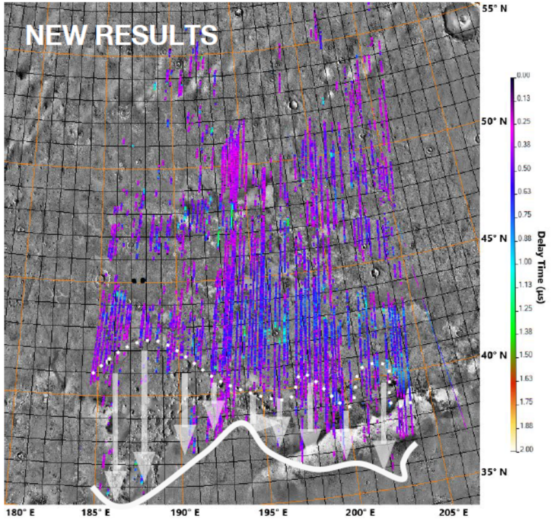
- We extended reflector mapping of Bramson et al. [2015], including southward extension to ~ 35.6°N.
- Using 23 topographic features, we find real dielectric permittivity between 3 and 6, with a median of 5, above the shallow reflector.
- Our revised permittivity allows a large fraction of non-ice material* without ruling out ice presence.

Previous state-of-the-art mapping in Arcadia Planitia [Bramson et al. 2015]:



This work:

- *Increased coverage*
- *Refined dielectric constants (material composition)*
- *More-equatorward detections*



* See also Campbell & Morgan [2018].

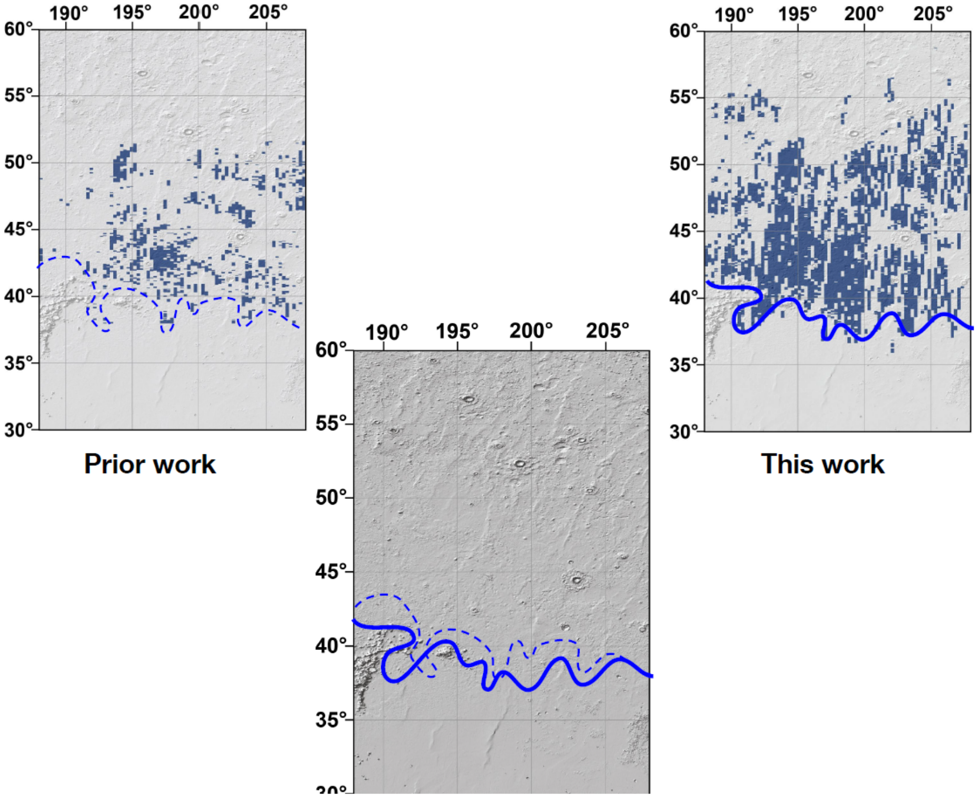
Slide credit: Than Putzig (PSI)

Slide credit: Than Putzig (PSI)

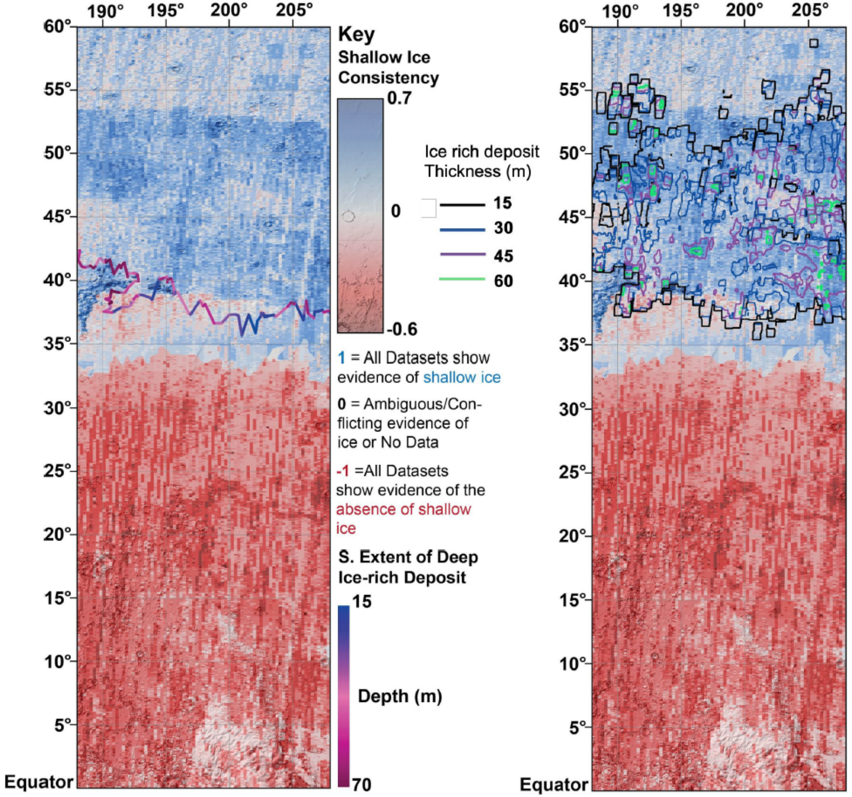
Consistency:
Integrating shallow + Deep

1. Prior State of Knowledge
2. Methods
3. Arcadia Planitia Results
4. Expanded Study Plans

SHARAD: Depth of Potential Icy Deposit

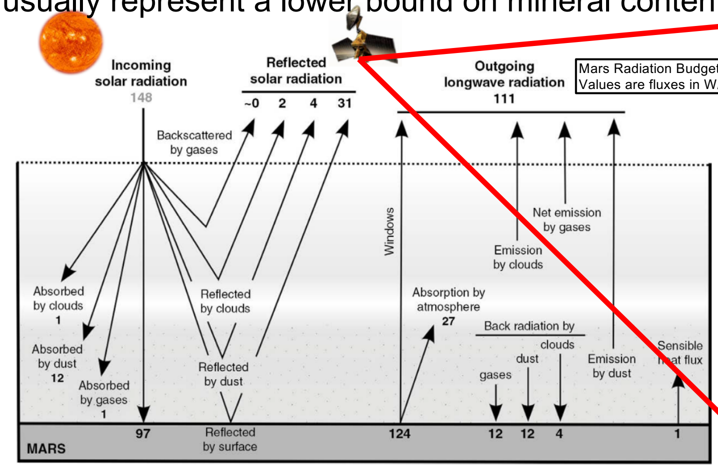


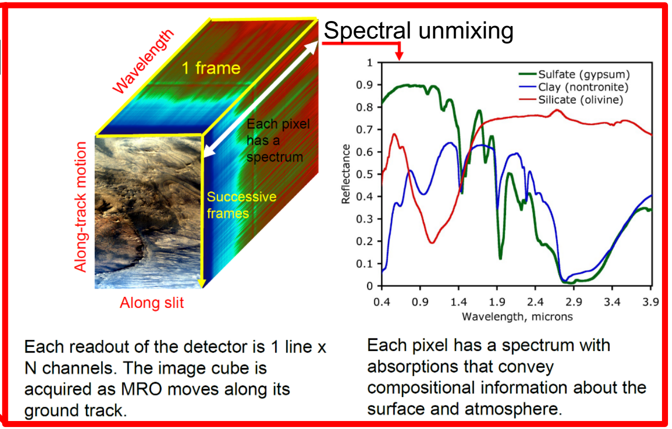
Consistency: Shallow + Deep



Hydrated Minerals Mapping: Overview of Datasets Used

- Hydrated minerals mapping relies primarily on VNIR spectrometers: OMEGA (Mars Express) and CRISM (MRO)
  - These operate on the principles of reflectance spectroscopy: intensity of sunlight reflected from a surface pixel is captured over a range of wavelengths
  - Received signals need to be corrected for atmospheric conditions and spacecraft state at the time of observation
  - The method's reliance on reflected sunlight means that only mineralogical information within the top few microns of the surface can be captured
    - Thus, observations of the surface using this method focus on dust-free areas
    - Further, direct measurements from MER and MSL have shown that mineral concentrations measured from orbit usually represent a lower bound on mineral content measured in-situ





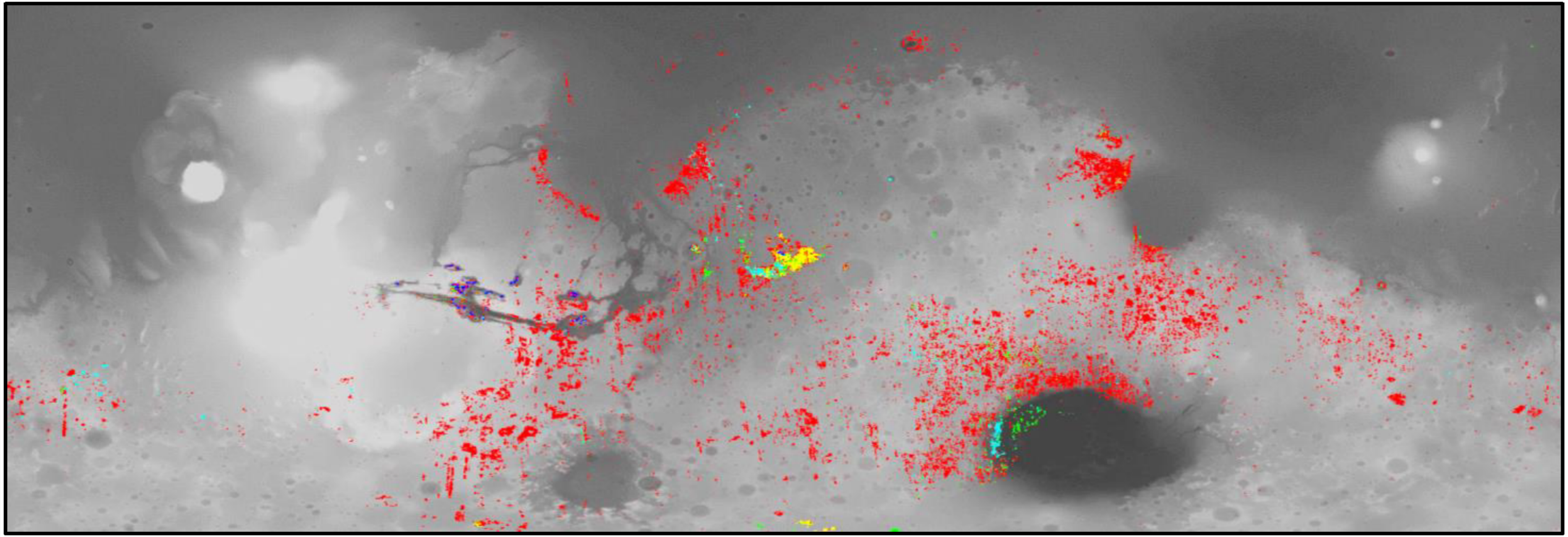
Images courtesy of F. Seelos (APL)

Minerals of Interest

- Two of the four types of water reserves examined by M-WIP are hydrated minerals. These are:
  1. Poly-hydrated sulfates (i.e. SO_4^{2-} salts with bonds to 3 or more water molecules)
  2. Phyllosilicate (clay, aka smectite) minerals
- Both hydrated minerals mapping teams are targeting these two types of minerals as well as other related groups
  - These classification schemes are based on the mineral library of each instrument (derived from similarities in spectral signatures), which impacts how their data is processed

Team 1 (Carter et al.) Targeted Mineral Groups for Mapping	Team 2 (Seelos et al.) Targeted Mineral Groups for Mapping	Example Mineral Detected on Mars
Fe/Mg Phyllosilicates	Fe/Mg Smectite	Nontronite (Iron Smectite): $(CaO_{0.5},Na)_{0.3}Fe^{3+}{}_2(Si,Al)_4O_{10}(OH)_2 \cdot \mathbf{nH_2O}$
Al Phyllosilicates	Al Smectite	Montmorillonite: $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot \mathbf{nH_2O}$
Hydrated Silica	Hydrated Silica	Opal: $SiO_2 \cdot \mathbf{n(H_2O)}$
Poly-Hydrated Salts	Polyhydrated Sulfate	Hexahydrite: $MgSO_4 \cdot \mathbf{6H_2O}$
Mono-Hydrated Sulfates	Monohydrated Sulfate	Kieserite: $MgSO_4 \cdot \mathbf{H_2O}$
Carbonates	Hydrated Carbonate	Artinite: $Mg_2CO_3(OH)_2 \cdot \mathbf{3H_2O}$
Serpentines	--	Lizardite: $Mg_3Si_2O_5(OH)_4$
Intimate Sulfate/Clay Mixtures rich in Fe/Mg physillosilicates and sulfates	--	--

Preliminary Hydrated Minerals Mapping Product



Fe/Mg phyllosilicates | Al phyllosilicates/hyd. silica | poly-hydrated salts
mono-hydrated sulfates | carbonates/serpentines | Sulfates + clays

Mars System Reconnaissance

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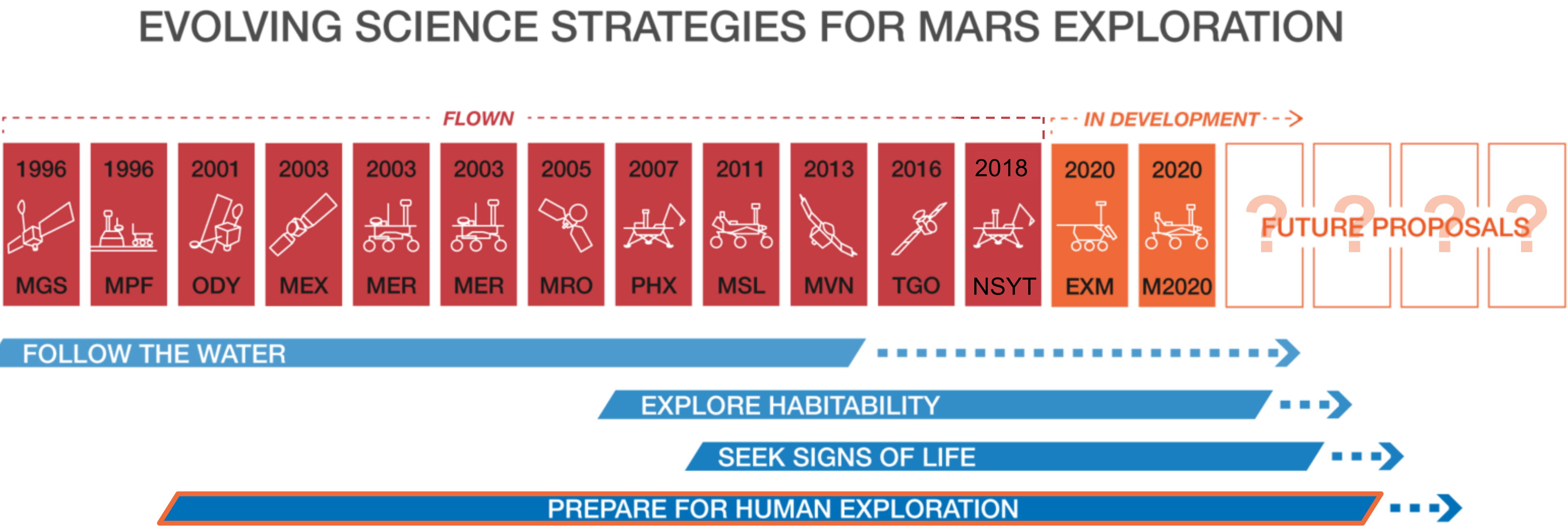
What data do we need to inform landing site selection?



What future missions are needed to gather this “reconnaissance” data?

Key Mars System Reconnaissance Data Needs

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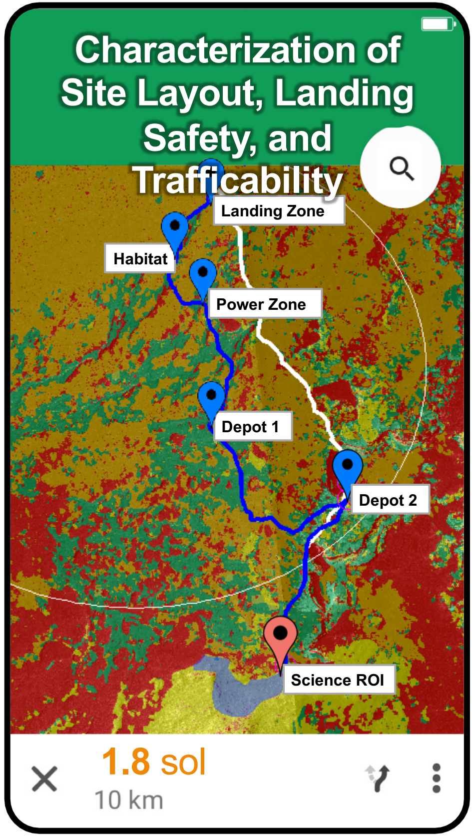

Mars System Reconnaissance – Enabling Mission Needs

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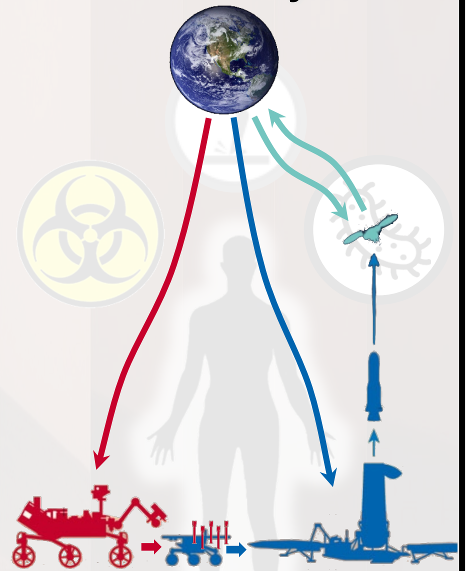
California Institute of Technology

Hazard Potential of Regolith and Dust on Humans and Systems

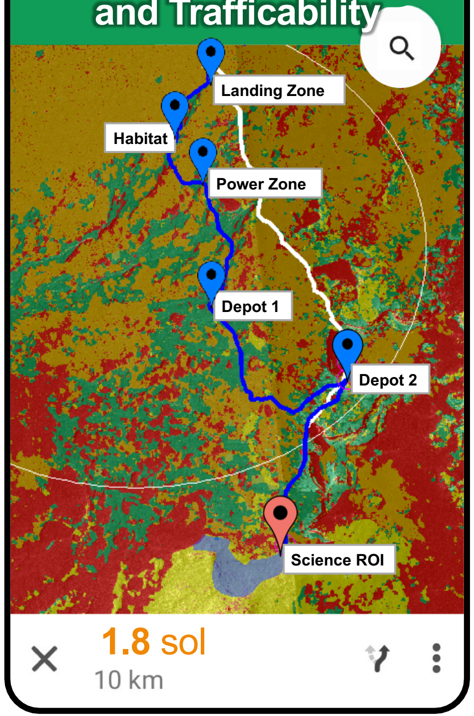


Analysis of Returned Samples

Characterization of Upper & Lower Atmosphere and Surface Pressure Conditions

Resource Mapping and Characterization

Characterization of Site Layout, Landing Safety, and Trafficability



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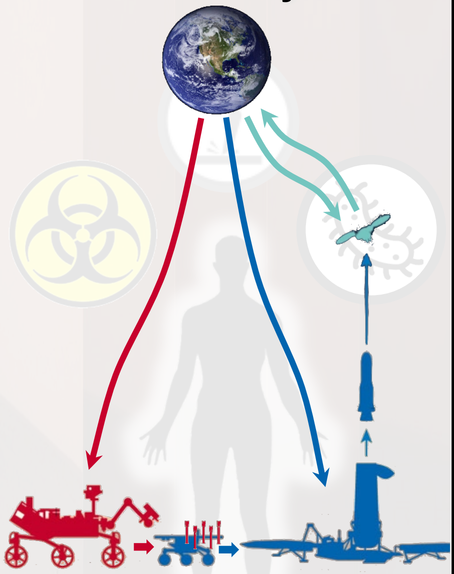

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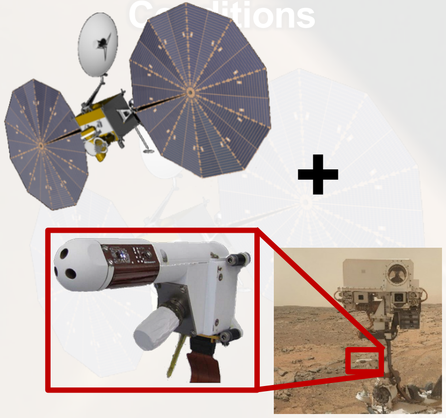
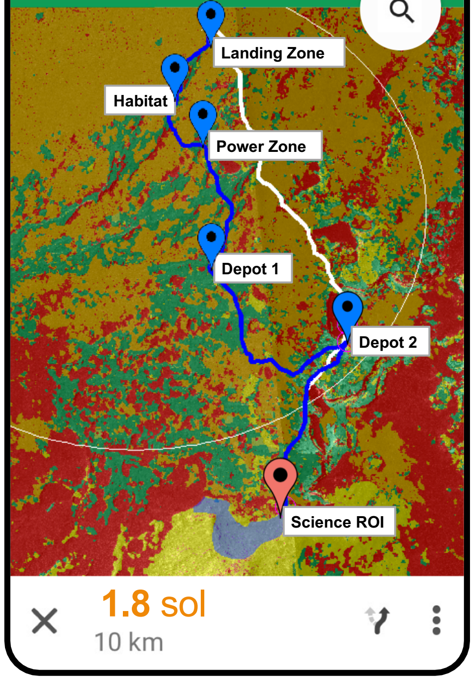


Orbiting Atmospheric Sounder Instrument + Surface Weather Packages

Resource Mapping and Characterization

Characterization of Site Layout, Landing Safety, and Trafficability



Mars System Reconnaissance – Enabling Mission Needs

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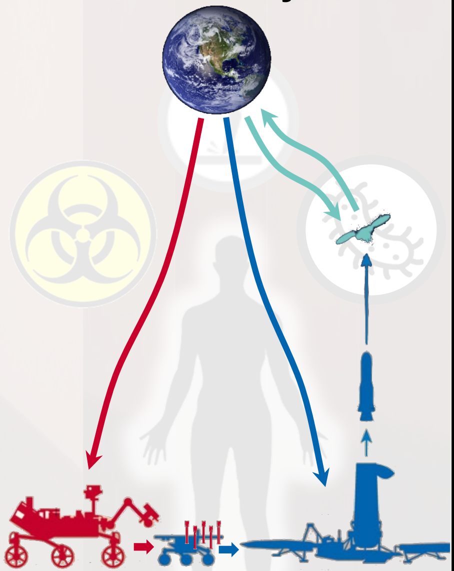
Hazard Potential of Regolith and Dust on Humans and Systems



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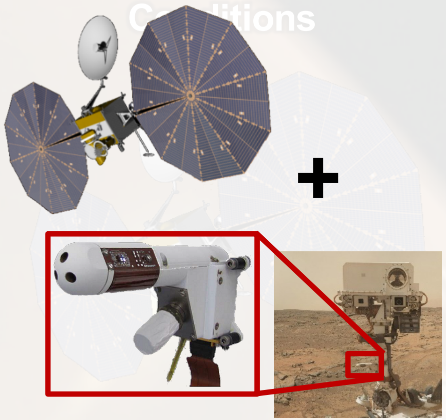

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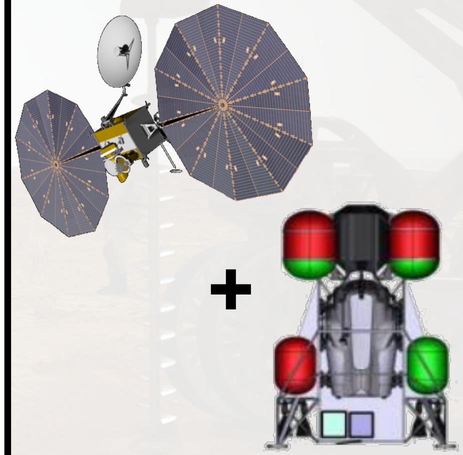
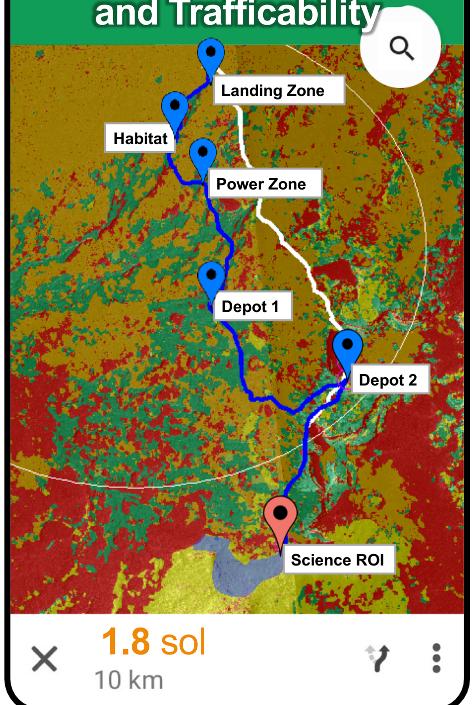


Mapping Orbiter + Ground-Truthing Lander(s)

Characterization of Site Layout, Landing Safety, and Trafficability



Mars System Reconnaissance – Enabling Mission Needs

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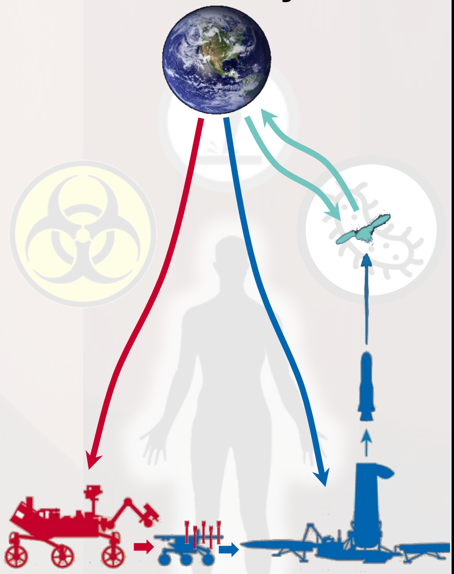

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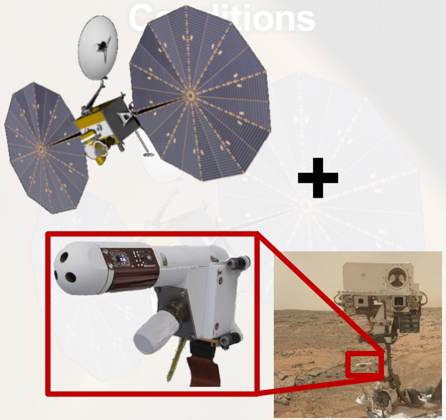

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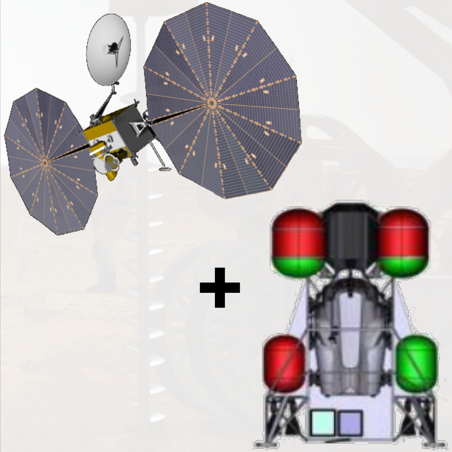

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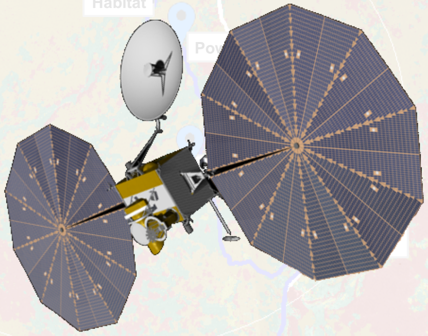
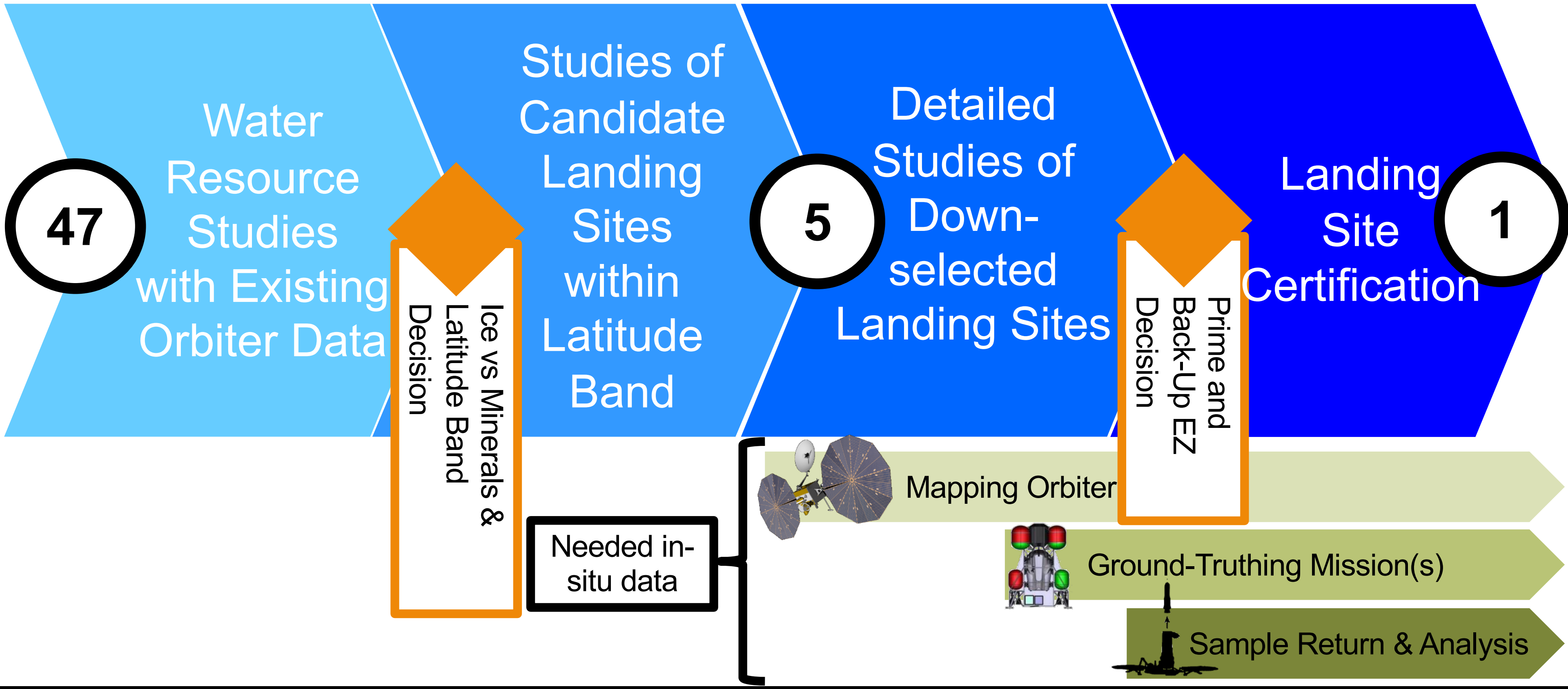


Orbiter with High Resolution Imager

Notional Path Forward for Mars Human Landing Site Selection



Closing Thoughts

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- Politics drives architecture
  - Consider participation of commercial and international partners in your architecture as a means of increasing programmatic sustainability
  - How do you architect an exciting program that keeps the public and politicians engaged?
- For a Mars focused architecture Moon to Mars architecture, the community consensus is that anything that is done on the Moon should have direct traceability to Mars
  - As a result, you need to have a good idea as to what your Mars architecture is when architecting your lunar architecture
- Explicitly define what the desired initial and end state of your architecture is
  - Derive this from a set of high level programmatic/policy goals
  - Is it an Apollo style sortie, a research field station (like Antarctica), or a self-sustaining settlement?
  - What are your figures of merit / evaluation metrics?
    - Exploration distance covered? Crew time? Cost? Commercial engagement / economic development?
- What is an acceptable level of risk?
  - How much are you willing to spend to reduce the P(LOM) or P(LOC) by what amount?
    - Applies to both robotic precursor reconnaissance missions as well as additional similarly or dissimilarly redundant systems

Thank You!

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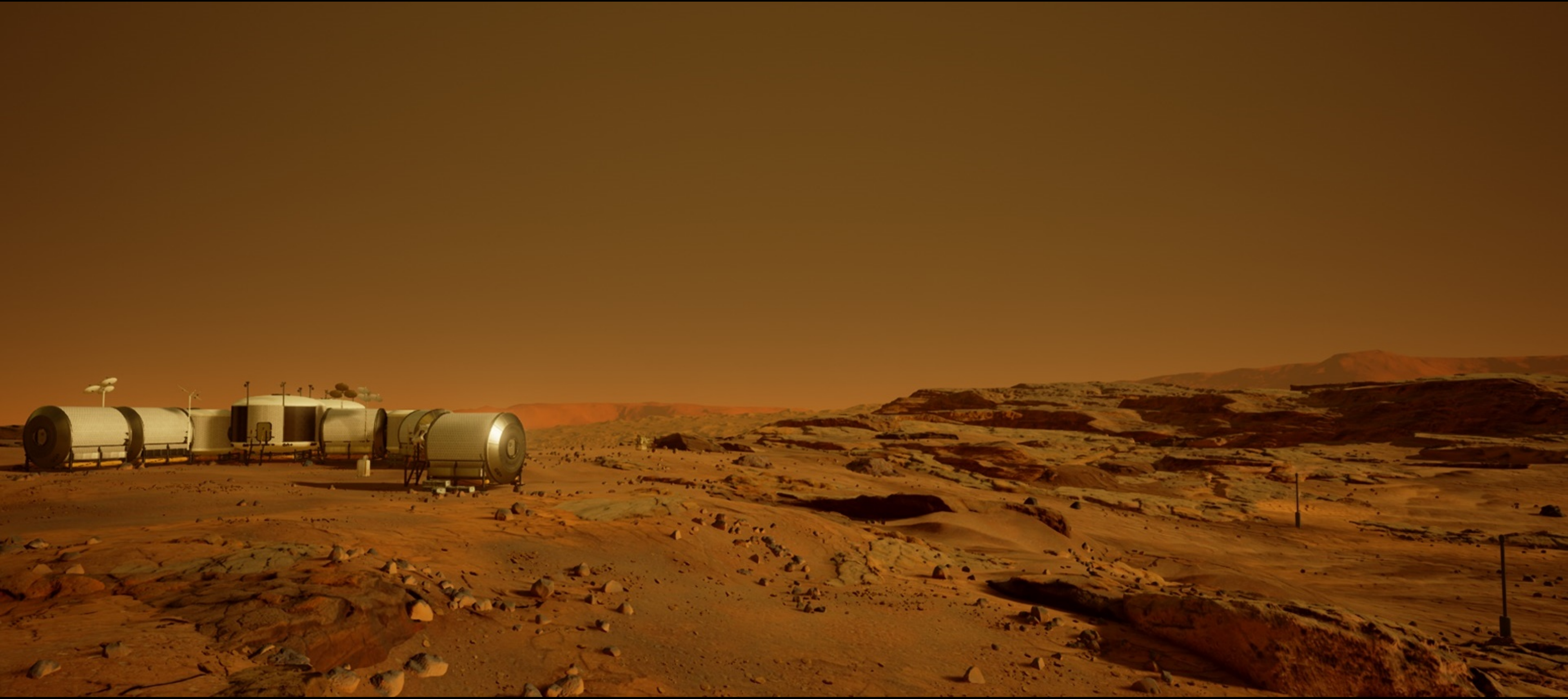

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