REVOLUTIONIZING ACCESS TO THE MARS SURFACE: KEY TECHNOLOGY NEEDS IDENTIFIED FROM THE KISS REPORT TO ENABLE LOW-COST MISSIONS TO THE SURFACE OF MARS.

B.L. Ehlmann[1], C. J. Culbert[2], A.A. Fraeman[3], [1]California Institute of Technology, [2]NASA Johnson Space Center, [3]Jet Propulsion Laboratory, California Institute of Technology

Motivation: Mars has a uniquely accessible historical archive in its rock and ice record, and it is the best place in our solar system to study the long-term evolution of a habitable terrestrial planet. It is also is the only habitable planet in the solar system that humans could explore and occupies a unique place in global culture. The U.S., Europe, China, India, and the United Arab Emirates are all currently operating spacecraft at Mars. In preparing to conduct the first sample return, now is prime time to consider "what comes next?".

Many scientists would propose landed missions to Mars if technologies discussed herein were available. As highlighted by the Mars Architecture Strategy Working Group report (2020), the depth and breadth of our current scientific understanding of Mars leads to a set of priority science questions that require measurements that only achievable on the surface by visiting multiple discrete locations (Fig. 1). The technological challenge going forward is therefore not simply to land payloads of various sizes on Mars—this ability has been demonstrated—but to do so at an average per mission cost that enables multiple landings to answer the many scientific questions that require surface access at different locations (Table 1). The next revolution in our understanding will come from a comprehensive exploration of the diversity that we already know exists at Mars.

Under the auspices of the Keck Institute for Space Studies at Caltech, we convened a group of Mars scientists and engineers, representing multiple academic institutions, NASA Centers, and commercial companies to address the challenge of revolutionizing access to the Mars surface (full report online). We found a strategic programmatic approach is needed to align the incentives for continuity of Mars exploration leadership and more affordable, frequent Mars surface exploration. Advances in technology along with new commercial services models for communications, delivery to orbit, and landing could allow a line of

Figure 1. Crucial scientific measurements for understanding the Mars system require access to and interaction with the Mars surface.

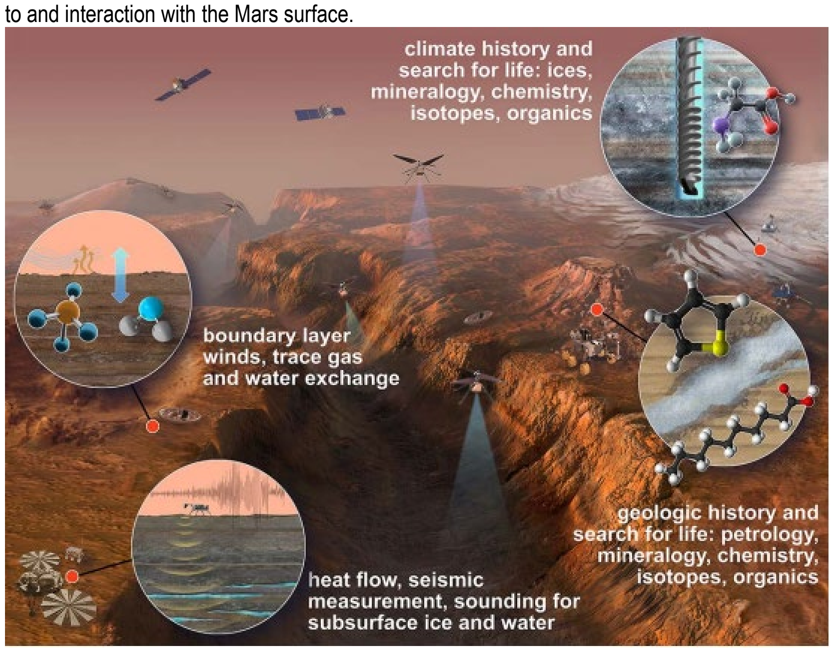

Table 1. Classes of lander capability that could satisfy science objectives. Progress on many objectives can be attained with smaller systems, thanks to miniaturization of instruments and lander bus technologies.

Mission Science Objective	Small, hard fixed lander	Soft fixed lander	Aerial mobility	Rover mobility	Large (optionally mobile)
Surface-atmosphere boundary layer interactions (incl. trace gas measurements)	✓	✓	✓	✓	✓
Geophysics (subsurface ice/water w/ resistivity, GPR, Seismo, magnetism)	✓	✓	✓	✓	✓
Polar Layer Deposit climate record determination		✓	✓	✓	✓
Mid-latitude ice sampling for characterization		✓		✓	✓
Geology Field Explorer for characterizing ancient habitable environments, environmental change			✓	✓	✓
Geochronology for Martian and solar system chronology				✓	✓

lower cost Mars Exploration Program missions.

Technology Needs: Small fixed landers (5kg min. payload) and soft fixed or modest mobility landers (20kg min. payload) allow accomplishing most science objectives (Table 1). Technologies, important to landed Mars missions, are shared with terrestrial commercial sectors and the growing lunar economy, though Mars poses unique challenges that may drive focused technology investments in key areas (Table 2).

Programmatic Needs: Technological advances can lower cost, but factors in addition to new technical approaches must adopted to fully activate potential stakeholders and their capabilities at Mars. Growing numbers of commercial, international, and academic institutions have capabilities to conduct all or portions of Mars missions. Frequent, Affordable, Bold (FAB), constitutes a multi-pronged programmatic approach to improve access to the Martian surface by engaging emerging stakeholders and creating an opportunity to utilize an economy of scale where there currently is none. FAB emphasizes a predictable high cadence of missions, low program cost by changing implementation partnership approaches as well as reducing per mission cost, and bold execution, using new technologies that permit the affordable and frequent elements, compensating programmatically for higher risk (Fig. 2). Programmatic strategy is essential as is leveraging present trends in the commercial space industry at LEO and the Moon and international interest in Mars.

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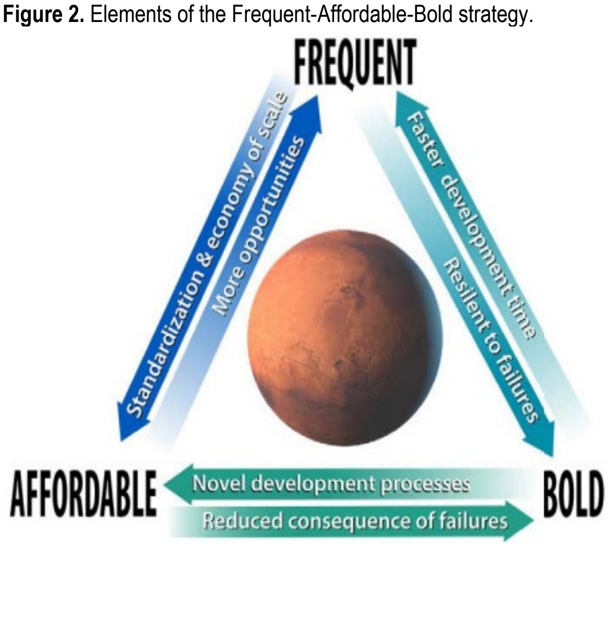
Figure 2. Elements of the Frequent-Affordable-Bold strategy.



For the full report:

https://kiss.caltech.edu/final_reports/Access2Mars_final_report.pdf Keck Institute for Space Studies (KISS), 2021, Revolutionizing Access to the Mars Surface. Culbert, C.J., Ehlmann, B.L., Fraeman, A.A., editors. Final Workshop Report for the W.M. Keck Institute for Space Studies, Pasadena, CA, USA, doi: 10.7907/d1sm-mj77.

Table 2. Key Technologies Enable Low-Cost Mars Surface Missions
Mobility systems: Physical mobility system design (actuators, wheel design) and autonomy (surface navigation, sensors, fault detection and recovery) are common across Mars, lunar, and terrestrial roving systems, with similar terrain and environmental requirements. Similar synergies exist for rotorcraft applications on Mars and Earth.
Entry Descent and Landing (EDL): While Mars' thin atmosphere introduces many unique aspects, certain technologies can be leveraged across lunar, Mars, and other planetary applications. Sensors for descent guidance (IMUs, radar, Doppler LiDAR), terrain-relative navigation (vision systems), and hazard avoidance (visual and LiDAR systems) span diverse target body needs
Rough landers: DoD makes significant investments in impact attenuation systems for large airborne payload delivery, as well as very high g-load systems for smart munitions, including sensors and electronic packaging. Both of these areas have high relevance for the design of low-cost hard landers and instruments for Mars.
Telecommunications: Commercial Earth telecom offers technologies adaptable to Mars needs. NASA should seek to maximize synergies between lunar and Mars relay architectures. Relay for landed missions is essential for high Mars data return. Direct-to-Earth (DTE) links for Mars relay satellites will have more challenging requirements than similar lunar relay satellites, driving the need for higher power, higher-gain components on the relay orbiter DTE links. However, proximity links between landed missions and relay satellites share characteristics, with common desire for high bandwidth, high connectivity, and low user burden
CubeSat and SmallSat systems: Thousands of CubeSat and SmallSat designs have been created and flown. Many aspects of these systems are available as commercial, off-the-shelf items. Subsystems including avionics, power, and navigational cameras are applicable to use on Mars and represent a fast, cheap way to take advantage of an existing commercial product.
Commercial electronics component technologies: High-performance processors and sensors, driven by the automotive and cellphone industries, offer significant opportunities for large increases in capability with dramatic reductions in mass, volume, power, and cost. The Mars2020 Ingenuity helicopter successfully leveraged a commercial processor, commercial flight micro-controllers, Li-ion batteries, COTS cameras, and radio systems.
Software Systems: Autonomous navigation, artificial intelligence, and machine learning technologies from commercial applications can support a wide range of capabilities and behaviors needed by autonomous robotic explorers, necessary at Mars because of the significant communications delay to Earth. Infusion of open-source software from the research community can leverage significant external investments and speed mission development cycles. Common flight software frameworks such as NASA's Core Flight System (cFS), or similar terrestrial frameworks like ROS 2.0, can minimize the development of common mission software capabilities (e.g., logging, file access, time-keeping).