The Mars Atmospheric and Polar Science Mission

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Authors:
Scott Guzewich (NASA GSFC, 301-286-1542, scott.d.guzewich@nasa.gov)
James Abshire (NASA GSFC)
Lynn Carter (University of Arizona)
Daniel Cremons (NASA GSFC)
Lavender Hanson (University of Maryland/NASA GSFC)
David Hollibaugh Baker (NASA GSFC)
Der-you Kao (NASA GSFC)
Alain Khayat (University of Maryland/NASA GSFC)
Brook Lakew (NASA GSFC)
Emily Mason (NASA GSFC)
Rafael Rincon (NASA GSFC)
Haris Riris (NASA GSFC)
Michael Smith (NASA GSFC)

Key Point:

We encourage the Planetary Science and Astrobiology Decadal Survey 2023-2032 to include a Mars orbiting mission, with science goals and capabilities comparable to MAPS, in the New Frontiers program. MAPS would achieve science objectives of both astrobiology and planetary science that are worthy of the New Frontiers program and is technically and fiscally achievable in the next decade of planetary science. Such a mission would represent a great leap in understanding modern and ancient Mars and prepare us for human exploration of the Red Planet.

1 Introduction

We, the authors of this white paper, present the Mars Atmospheric and Polar Science mission (MAPS) concept to the 2023-2032 Planetary Science and Astrobiology Decadal Survey and advocate that a Mars orbiter mission with comparable science goals and capabilities be included within the New Frontiers program during the next decade. In 2019, we conducted a mission concept study at the NASA Goddard Space Flight Center (GSFC) Mission Design Laboratory (MDL) and developed a point-design for the MAPS mission. The resulting point-design was subjected to a thorough parametric costing and found to be within the expected New Frontiers cost cap for FY2025 with standard (~30%) cost margins.

MAPS would address a litany of priority Mars Exploration Program Analysis Group (MEPAG) science goals [1] regarding the modern climate system, the polar caps and subsurface water ice, possibilities of refugia for extant life, and geology, geochemistry, and geophysics. Our baseline instrumentation suite (see Section 3.1) would consist of 4 instruments, each with capabilities not yet flown to Mars that will be ready for flight within the next decade of planetary science. Additionally, data from MAPS would fill numerous strategic knowledge gaps for human exploration of Mars through reducing risk for human landing and launch from the surface, identification and confirmation of special regions, and precise identification of water ice resources available to human explorers.

MAPS would achieve science objectives of both astrobiology and planetary science that are worthy of the New Frontiers program and is technically and fiscally achievable in the next decade of planetary science.

2 MAPS Science

MAPS addresses the identified focus in the planetary science community that Martian polar science, the history of its past climate, and the cycles of water and other volatiles represent keys to understanding Mars and other terrestrial worlds in the Solar System and potentially beyond (e.g., [2]). The Ice and Climate Evolution Science Analysis Group (ICE-SAG), chartered by MEPAG, examined a variety of different mission implementations to advance Martian polar and climate science [3]. MAPS represents one potential such implementation, a New Frontiers-class orbiter, that would substantially address its identified priority science areas. Specifically, the MAPS mission was designed to address the following science questions:

- How does shallow ground ice record climate change and is it related to the polar caps?
- Where does shallow pore-filling ice occur?
- What is the global atmospheric circulation?
- What role do volatiles have in recurring slope lineae formation?
- How do the surface and atmosphere interact?
- What environments were habitable in the past?
- What drove past environmental transitions?

These science questions fall into 3 broad science themes: Amazonian Climate Evolution, Dynamic Processes on Modern Mars, and the Evolution of Martian Volatiles Through Time.

A) Amazonian Climate Evolution

The polar layered deposits (PLD) of Mars are believed to record a changing climate over the past millions of years, likely tied to changes in planetary obliquity, eccentricity, and other orbital variations [4]. Existing radar sounding of the planet has detected discrete layering in the polar caps at scales of 10s to 1000s of m, which appear distinct from much finer scale layering seen in outcrops and edges of the polar caps in orbital imagery (e.g., [5], [6], [7]). At mid-latitudes, buried water ice has been found by the Shallow Radar (SHARAD) and Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS), which appears to be a sign of past glacial activity and climate variations, while also being an appealing target for in situ resource utilization for future human explorers (e.g., [8], [9], [10]). Yet, existing measurements have not been able to precisely determine the depth, and hence volume, of subsurface ice, its connections to the polar caps, and whether it is exchanging with the atmosphere.

A variety of evidence from orbit, including the radar-measured dielectric constant of the surface regolith, to the observation of ice in recent impact craters, the morphologies of such craters, and visible ice layering in escarpments has shown that a pore-filling ice mantle is present through the martian mid-latitudes [11, 12]. The Phoenix lander dug into this ice-rich regolith when it landed at higher northern latitudes [13]. The total volume of this water is unknown, nor how it varies in depth as a function of latitude. Existing orbiting radar have wavelengths that are too long to be able to isolate these apparently thin layers. Fresh impact craters or landslides are too stochastic and rare to allow for a comprehensive evaluation of martian subsurface ice deposits.

MAPS will directly measure the global extent and volume of shallow subsurface H_2O and CO_2 ice on Mars. MAPS will measure how these reservoirs change on seasonal timescales, or with sufficient mission duration, on interannual timescales. Measuring these ice reservoirs and how they change will help isolate the processes that control their deposition and removal and the mechanisms that caused their original emplacement.

B) Dynamic Processes on Modern Mars

The atmosphere connects the otherwise disparate portions of the martian climate system. Precipitation hasn't likely fallen nor has substantial surface liquid water been present on Mars in billions of years and hence all transport of water and other volatiles is done through solid and gas phase transitions. This makes understanding the atmospheric circulation critical to understanding the entire climate system in the modern day and providing a benchmark for extrapolating to past climate regimes. Despite a long and growing record of atmospheric temperature and aerosol (dust and water ice) opacity, the atmospheric circulation has never been directly observed. This is due to the paucity of global wind measurements [14]. Existing measurements of martian winds are from isolated landers [16], occasional ground-based telescopic measurements, and more recently, upper atmospheric/exospheric wind measurements from the MAVEN spacecraft [17]. Yet these are all woefully insufficient to diagnose the atmospheric circulation in even the coarsest way. Model predictions of wind patterns do not agree with each other and estimates of wind fields from temperature measurements have critical deficiencies at low latitudes and altitudes.

MAPS will measure the global atmospheric wind field, in conjunction with aerosol (dust and water ice) opacities and water vapor abundance, and thus directly diagnose the transport of volatiles between their reservoirs in the climate system as well as heat and momentum. MAPS will measure the material and energy fluxes that move through the martian climate system.

The record of active processes identified by the Mars Reconnaissance Orbiter (MRO) have shown Mars to be a dynamic place. Recurring slope lineae (RSL) are one of the most intriguing of those phenomena, with a variety of mechanisms postulated to create them (e.g., [19, 20]. While RSL may not be signs of ongoing liquid water flows on the surface, water may still play a role in their formation [21] and in the formation of other surface features. But existing instrumentation on MRO and other spacecraft are not sufficient to diagnose the presence of liquid brines or the minerals that may have formed in the presence of liquid water.

MAPS will directly search for signs of liquid brines on the surface or shallow subsurface and map the global distribution of surface mineralogy at high spatial resolution, capable of resolving small features such as RSL.

C) Evolution of Martian Volatiles Through Time

Understanding how water has shaped Mars throughout its history has been a driving goal of planetary science since the founding of NASA. We know liquid water was widespread on its surface at times during the Noachian and early Hesperian periods of martian history 3-4 Gya. Yet vital questions remain regarding how Mars' climate evolved and water became scarce and then absent on the surface. Much of that record has been later covered by subsequent volcanic activity and 3 billion years of wind-driven erosion and aeolian processes. Being able to see below the surface mantle of dust, sand, and volcanic flows would allow us to better understand how environments transitioned through time and better isolate the order of those transitions.

MAPS will globally map the planet's mineralogy and map the planet at high spatial resolution in radar wavelengths that will allow us to see through the surface regolith overburden to track the evolution of martian volatiles through time. MAPS will illuminate the later volcanic history of the planet and determine compositions and distributions of igneous rocks.

D) Traceability to MEPAG Science Goals and 2013-2022 Planetary Science Decadal Survey

MAPS science goals directly trace to the 2013-2022 Planetary Science Decadal Survey's [22] high priority science goals for Mars regarding the "Processes and History of Climate" and "Evolution of the Surface and Interior." MEPAG has expounded on these broad goals with their most recent update [1] and MAPS science objectives help address aspects of all 4 MEPAG Science Goals. Through a direct search for liquid brines and past aqueous alteration, MAPS would help MEPAG Goal I (Investigation A2.1) regarding the search for life and its geologic context (Goal I, A2.5). MAPS would make the first global measurements of wind, which

MEPAG terms a “high priority for this entire Sub-Objective” (Goal II, Investigation A1). Concurrent measurements of wind, temperature, and aerosols would allow us to measure fluxes of heat, energy, and material through the system (Goal II, A2.1). Monitoring surface, subsurface, and atmospheric reservoirs would help illuminate exchange processes (Goal II, A2.2). A major objective of MAPS directly follows from MEPAG Goal II Sub-Objectives B1 (and its associated investigations) regarding the climate history of the polar regions and B2 regarding the mid-latitudes. Thermal infrared spectroscopy and synthetic aperture radar observations of Mars by MAPS will help constrain the ancient water cycle (Goal II, C2.1). Goal III Sub-Objective A1, regarding characterizing Mars’ water and volatile record as expressed in geology would be substantially advanced by MAPS observations. Similarly, MAPS would help constrain the timing of ancient environmental transitions (Goal III, A3.1). Many of these science goals are expressed in the ICE-SAG report [23].

Lastly, MAPS would substantially fill numerous strategic knowledge gaps [24] for human exploration and MEPAG Goal IV of preparing for human exploration of Mars. Of note, MAPS measurements of subsurface ice would identify the depth, purity, and volume of accessible water resources. MAPS observations of global winds would reduce risk for entry, descent, and landing and launch from the surface.

3 Technical Implementation

MAPS was designed through a NASA GSFC Mission Design Laboratory (MDL) study, with a smaller secondary study to make design trades and refine the point-design of the spacecraft. MAPS was assumed to launch in November 2028 on a SpaceX Falcon Heavy (Recoverable) with an arrival at Mars in September 2029 and beginning of a 1 Mars year primary science mission in June 2030. The primary science orbit is a 93° Sun-synchronous orbit at 300 km altitude with a 9 am equator crossing local time. Thus, the orbit is MRO-like except for the local time difference, which is specified to observe the early morning time when surface liquid brines are most thermodynamically stable. MAPS would carry an Electra relay package for communication with surface spacecraft.

Upon conclusion of the study, GSFC costing experts completed a parametric costing of the mission using the PRICE-H tool. They found a point estimate of $505M in FY19$, with an additional $170M for instruments, which is within the expected FY25$ New Frontiers limit with standard ~30% cost reserves for the spacecraft and instruments (launch costs and Phase E science operations not included).

3.1 Instrumentation

To address our science goals we included 4 instruments on the spacecraft: the Mars lidar for global climate measurements from orbit (MARLI), the Space Exploration Synthetic Aperture Radar (SESAR), a multispectral thermal infrared imaging spectrometer, and a visible-near infrared wide angle camera. We discuss each in turn:

1) MARLI

The Mars lidar for global climate measurements from orbit (MARLI) is a direct-detection atmospheric Doppler lidar operating in the near-infrared (1064 nm) to detect line-of-sight wind speed and aerosol (dust and water ice) extinction in the atmosphere [25]. For our study, we assumed MARLI was mounted on a tilt-table platform that allows it to observe the vector-resolved wind speed in the atmosphere. MARLI is able to discriminate the wind speed from the surface to ~40 km with precision of ≤4 m/s and a vertical resolution of ~2 km, with comparable vertical resolution for aerosols and 10% or less relative error in aerosol extinction. Importantly, due to MARLI's backscattering measurement technique, the instrument is *more sensitive* during dust storm conditions and is still able to retrieve the wind speed down to the surface. The high vertical resolution of MARLI and the ability to sense all the way to the surface allows key science questions regarding global transport of dust and water vapor to be addressed.

MARLI has been developed through the PICASSO and MATISSE programs and was expected to reach TRL 6 in June 2020, prior to the COVID-related suspension of work at NASA GSFC. MARLI employs a 50 cm telescope, with an instrument mass of ~45 kg, and uses 90 W of power (both power and mass including the tilt table). MARLI produces 50-100 kb/s data and would operate at 90%+ duty cycle in the baseline MAPS concept of operations to ensure global coverage.

2) SESAR

The Space Exploration Synthetic Aperture Radar (SESAR) is a polarimetric beam-forming P-band SAR currently being developed under the MATISSE program, and expected to reach TRL 6 in summer 2022 [26]. SESAR would use a 70 cm radar wavelength, optimized for high resolution imaging and sounding of the shallow subsurface of Mars. In regolith, SESAR is expected to reach ~10 m of depth and 10s of m depth in water ice. Through retrieval of the dielectric constant of the backscattering material, SESAR can distinguish between liquid brines, ice, and regolith at spatial resolutions of O(2 m). SESAR's polarimetric capability is key for separating mantling units of dust, sand, and regolith from geologic features of interest that lie below. SESAR also is capable of operating in a sounder mode with a vertical resolution of ~2 m.

On MAPS, SESAR would use 240 antenna elements on 6 individual panels that would fold out after spacecraft separation from the launch vehicle. Total mass of the instrument, including the electronic assembly is approximately 300 kg with an orbit average power of 112 W. For MAPS, we targeted a duty cycling that will allow the spacecraft to manage the data generated by the instrument while also achieving all science goals. At medium resolution, ~21 m/pixel on the surface, SESAR would map the planet over 50 times, with 23% of the planet covered at high resolution (~2 m/pixel), over the duration of the mission. With a 10% duty cycling, SESAR generates ~3.8 Gb/orbit.

3) Thermal Infrared Imaging Spectrometer

We have included a thermal infrared imaging spectrometer (TIIS) to examine surface mineralogy and geochemistry and atmospheric temperature, water vapor, and aerosol abundances. We did not specify a particular instrument, but one is being developed at a potential partner US-based institution that is expected to be ready for flight in 2-3 years with modest cost and effort. The TIIS would sample the 6-25 μm spectral range at 10 cm^{-1} spectral resolution in pushbroom mapping or gimballed targeted observations. TIIS would achieve 70 m/pixel surface resolution and 2 km vertical resolution (with averaging, ~350 m/pixel) when observing the atmospheric limb. This surface resolution is sufficient to study RSL, identify pore-filling ice, and surface mineralogy at the scale of a surface rover traverse.

We have used size, mass, and power dimensions from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard MRO, with the expectation that TIIS would be comparable when flown. Including the data processing unit, TIIS would mass 30 kg, and draw 15 W operating and 30 W peak power. TIIS generates 2.5 Mb/s in mapping or atmospheric mode and 77 Mb/s in targeted mode, with an expected 4% duty cycle.

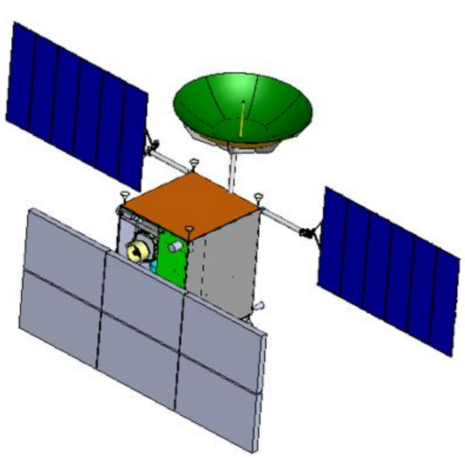
4) Visible-Near IR Wide-angle Camera

The Visible-Near IR Wide-angle Camera (VNIR-WAC) is based on the Mars Color Imager (MARCI) camera onboard MRO, but with enhanced capabilities for MAPS' science goals. Again we did not specify a particular instrument, but one is in development at a potential partner institution. It would include 2 pushframe imagers, one in the visible with 6 total channels (including one channel in the UV) and one in the near-infrared with 6 channels between 1.1-1.6 μm. Both would have a 150° field of view, allowing it to map the surface and the limb of the atmosphere at <0.5 km/pixel and 3-6 km/pixel, respectively. It would operate at 50% duty cycle (i.e., only on the dayside of the planet) to map surface ice distributions and atmospheric phenomena on a daily basis.

It's total mass is 0.8 kg including the interface adapter and would use 2 W power. It's data rate is nominally 0.5 Mb/s when operating.

3.2 Spacecraft

The spacecraft design (Figure 1) was driven, in large part, by the ability to carry SESAR (large gray panels in Figure 1) and return the data generated by the instruments. Given our aim to design a New Frontiers-class Mars orbiter, the spacecraft is built largely to Class B, with some subsystems at Class C, redundancy. The spacecraft dry mass is 1800 kg, including contingency and instruments, with an additional 1300 kg of propellant, for a total launch mass of 3100 kg, which is well within the capabilities of the launch vehicle. We have assumed a Lockheed Martin A2100 spacecraft bus to accommodate the instruments and the fuel tanks. The spacecraft is 3-axis stabilized to allow the nadir-deck (instrument deck) of the spacecraft to maintain pointing at the planet. Planetary protection was accounted for based on existing requirements for Mars orbiter missions.



The instruments and spacecraft require 1150 W of power, including contingency, at Mars which is supplied by 23 m^2 of solar panels in two foldout wings. Power is managed with a 100 Ahr lithium-ion battery, sized to account for eclipse periods behind the planet. The solar panels are articulated to maintain Sun pointing. The propellant provides 1.5 km/s of Δv, the majority of which is used during the Mars orbit insertion maneuver (1150 m/s). Aerobraking is also employed to circularize and lower the orbit periapse. Spacecraft stability and pointing parameters are driven by SESAR's pointing requirements and require 0.28° along track and 1.1° cross track stability, with pointing knowledge 1/10th of both those factors. These requirements have substantial margin with the star trackers and spacecraft attitude control systems.

Including 30% contingency and allowing for surface relay using the Electra package, the communication and data handling system was sized to manage 52 Gbits/day of science and engineering data. In the final design, a 3.7 m articulated high-gain Ka-band antenna was used with a 200 W traveling wave tube amplifier. This provides data rates of 830 kb/s - 10 Mb/s based on the Earth-Mars geometry and using the 34 m Deep Space Network antennas. Additionally, X-band omni and X-band medium gain antennas would be used for redundancy and uplink from Earth. Importantly, we evaluated the potential for optical communication. An early intermediate design for MAPS included a 2nd generation Deep Space Optical Communication terminal, which may be capable of up to 65 Mb/s downlink to Earth. Optical communication will have longer blackout periods during solar conjunction between Earth and Mars, and drives the design of the data handling system. In the final design, a radio frequency communication was baselined due to greater confidence in system parameters. The spacecraft includes 2.5 TB of onboard storage to manage science data and would return ≥95% of total mission science data.

4 Conclusion

We encourage the Planetary Science and Astrobiology Decadal Survey 2023-2032 to include a Mars orbiting mission, with science goals and capabilities comparable to MAPS, in the New Frontiers program. MAPS would achieve science objectives of both astrobiology and planetary science that are worthy of the New Frontiers program and is technically and fiscally achievable in the next decade of planetary science. Such a mission would represent a great leap in understanding modern and ancient Mars and prepare us for human exploration of the Red Planet.

5 References available at: https://bit.ly/2P5NWxf

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