A Discovery-class Mars Climate Mission

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1. Introduction

The Mars Exploration Program Analysis Group (MEPAG [1]) and other NASA committees (e.g., the Next Orbiter Science Analysis Group [NEX-SAG; 2]) have cited ***high-priority science knowledge gaps related to understanding the current Martian climate and weather.*** Understanding of weather and climate drivers, general behavior, stability and history could be improved through **a combination of high-TRL existing instruments, flown together on a focused "Mars Climate Mission"** or as part of a larger mission architecture. The information gained would provide new insights into present climate and weather, aid in understanding past climate, and be useful for future robotic and human exploration needs.

3. Instrumentation Concept

Our Mars Climate Mission would include a minimum of three instruments: a passive sub-mm limb profiler, a thermal infrared profiler, and a wide-angle camera.

Sub-mm profiler: A passive sub-mm limb sounding instrument is ideally suited to provide the needed wind, water vapor, and temperature profile measurements. The technique has high heritage in Earth-science, and dramatic advances in associated technology in the past decade (driven in part by the communications industry) enable significant reductions in needed power, mass and complexity. Such an instrument can make measurements both day and night, and in the presence of atmospheric dust loading, measuring between 0–80 km, at ~5 km vertical resolution[5]. [See companion poster **"A Sub-millimeter sounder for vertically measuring Mars winds, water vapor, and temperature."**]

Thermal IR profiler: To measure the vertical distribution of dust and water-ice aerosols in the atmosphere, a thermal IR profiler similar to the MCS aboard MRO [6] would be ideal and would also provide additional temperature and water vapor measurements to those from the sub-mm instrument, measured over a similar altitude range with comparable vertical resolution, both day and night.

Wide angle camera: Finally, a wide-angle camera such as the Mars Reconnaissance Orbiter's MARCI [7, 9] would facilitate placement of the other measurements into the big picture of weather patterns seen via global maps.

Resources: Such a payload would likely be in the 40 kg and $55M (not an official cost estimate) range and high TRL. Power 75-105 W, Data rate: 175-200 kbps

Enhancements: An enhancement would be to add a Doppler lidar for higher vertical resolution wind information, especially in the lower atmosphere where there is ample dust that can be used for the lidar backscatter.

2. Science Motivation and Objectives

Fortunately, Mars research has benefitted from several orbiting spacecraft that have characterized the Martian atmosphere fairly well in terms of temperature, pressure, dust and ice aerosols, and column water vapor amount. Additionally, the ExoMars Trace Gas Orbiter will measure profiles of the abundance of many key trace gases, and MAVEN is studying the upper atmosphere and its interaction with the space environment.

However, *water vapor and wind vertical profiles are very limited*, and existing temperature retrievals can be hindered by large amounts of aerosols [3]. Thus, *our objectives are first-time measurements of global wind and water vapor profiles, along with T, aerosols, and global imagery.*

Water vapor vertical distributions are important for understanding water cycling between ice and sub-surface reservoirs. Further, water vapor profiles along with simultaneous temperature profiles, even in the presence of dust and ice, are critical to understand cloud formation which has a surprisingly large radiative impact on the atmosphere[4].

Winds are almost completely unmeasured, yet are critical for understanding fundamental Martian processes driving the dust and water cycles. In addition, winds are desired for safe landing of robotic and human spacecraft. In lieu of actual measurements, global circulation model output is often used to aid in spacecraft and mission design, but the models are largely unvalidated against winds. Finally, measurements of T, aerosol and water vapor are needed simultaneously with wind measurements, to fully understand the impact of thermal forcing on wind, and the consequences for transport.

A finding of the NEX-SAG (Next Mars Orbiter Science Advisory Group) states: *"Observation of wind velocity is the single most valuable new measurement that can be made to advance knowledge of atmospheric dynamic processes. Near-simultaneous observations of atmospheric wind velocities, temperatures, aerosols, and water vapor with global coverage are required to properly understand the complex interactions that define the current climate."*

In order to obtain these measurements, **we propose a Mars Climate Mission concept**, that would include at a minimum three instruments: a sub-mm sounder, a thermal infrared profiler, and a wide-angle camera.

The MEPAG Goal II, "Understand the processes and history of climate on Mars" has two sub-objectives under Objective A, "Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under the current orbital configuration" that are directly addressed by this Mars Climate Mission. They are:

- Obj. A1: Constrain the processes that control the present distributions of dust, water, and carbon dioxide in the lower atmosphere, at daily, seasonal, and multi-annual timescales – **All three of the high-priority investigations are addressed by this mission**
- Obj. A4: Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs

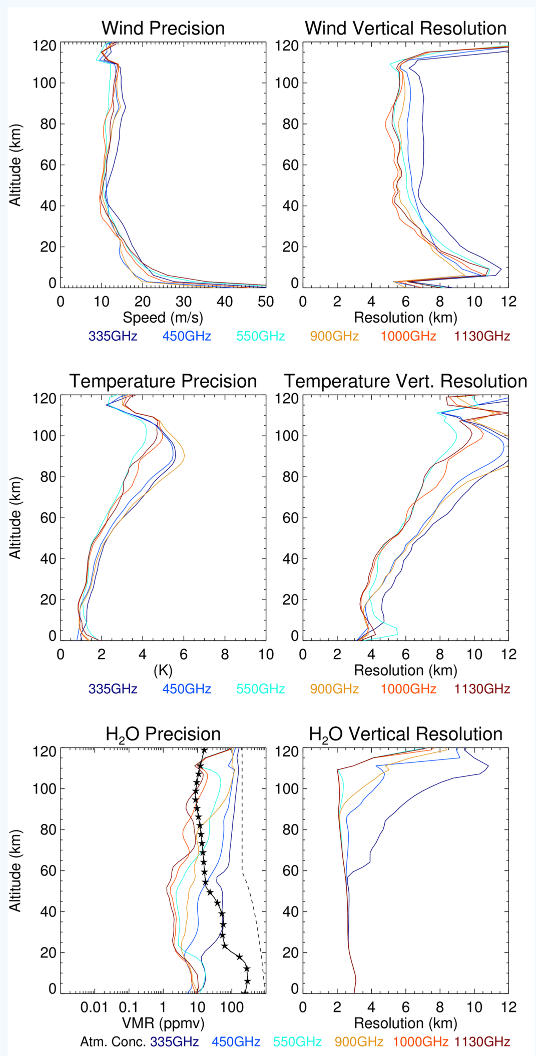
4a. Sub-mm profiler

Our Mars Climate Mission would include a minimum of three instruments: a passive sub-mm limb profiler, a thermal infrared profiler, and a wide-angle camera.

A passive sub-mm limb sounding instrument is ideally suited to provide the needed wind, water vapor, and temperature profile measurements. The technique has high heritage in Earth-science, and dramatic advances in associated technology in the past decade (driven in part by the communications industry) enable significant reductions in needed power, mass and complexity. Such an instrument can make measurements both day and night, and in the presence of atmospheric dust loading, measuring between 0–80 km, at ~5 km vertical resolution[5]. [See companion poster **"A Sub-millimeter sounder for vertically measuring Mars winds, water vapor, and temperature."**] Box 4b shows the precision and vertical resolution for wind, temperature, and water vapor as a function of altitude, for several frequency choices.

Resources for this instrument are estimated to be: Mass: ≤ 25 kg, Power: 50-80 W, Data rate: 20-100 kbps. TRL ~ 6.

4b. Sub-mm profiler precision/resolution



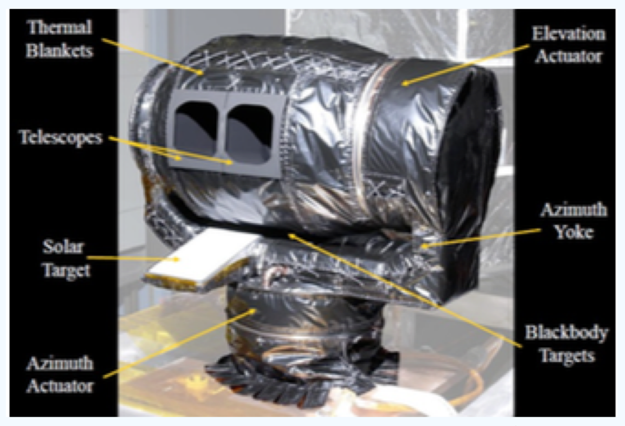
Estimated wind (upper left), temperature (middle left), and water vapor (lower left; black line with asterisks represents the assumed concentration) precision and vertical resolution for several frequency ranges considered in [5]. The expected vertical resolution is based on the full width, half height of the averaging kernel. The a priori uncertainty for wind is 100 m/s with a 10 m/s smoothing constraint. The corresponding numbers for temperature are 20 K and 2 K.

5a. Thermal IR profiler

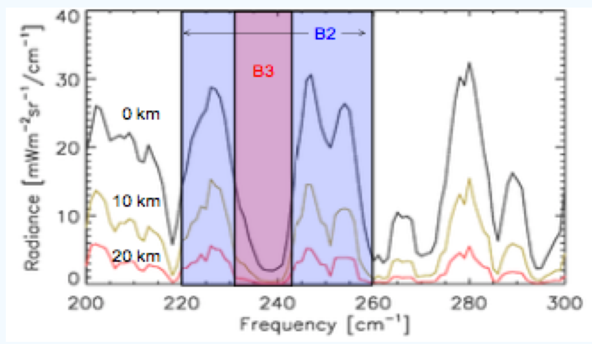
A thermal IR profiler, such as the Advanced Mars Climate Sounder (AMCS) would supplement the sub-mm profiler by providing vertical profiles of dust, water-ice, and CO_2 ice aerosols, as well as temperature and water vapor profiles [8]. Because the AMCS is modified from the currently flying MRO MCS experiment [6] and the Exo-Mars MCS experiment originally selected for the ExoMars Trace Gas Orbiter mission, this is a mature, low-cost, low-risk choice, with some mechanical and optical hardware already fabricated and available. The instrument nominally performs combined limb/nadir observations pointing forward along-track of the spacecraft velocity vector. It can also be pointed in any azimuthal direction to provide coverage at additional times of day as well as target views of other instruments such as the sub-mm sounder. AMCS measurements would cover a vertical extent of 0-90 km with ~5 km vertical resolution. Retrieval algorithms have high heritage from MRO/MCS [12, 13].

Resources for this instrument are estimated to be: Mass: 9 kg, Power: 18 W, Data rate: 2 kbps. TRL = 9.

5b. Thermal IR profiler figures



MRO MCS flight hardware during thermal/vacuum testing at JPL.



Limb radiance spectra showing water vapor bands in the far-IR with the positions of channels B2 and B3 indicated.

AMCS would use 8 spectral channels in the IR from 12-45 µm as well as a visible/near-IR channel distributed over 2 telescopes to fulfill its measurement functions. Each channel would consist of a linear array of uncooled thermopile detectors, which instantaneously measures a radiance profile when vertically pointed at the limb. Most channels are heritage from MRO/MCS. The combination of channels B2 and B3 would enable water vapor profiling by discriminating between water vapor and aerosols.

Telescope/ Channel #	Bandpass cm^{-1}	Band Center - µm	Measurement Function
A1	595 - 615	16.5	Temperature 0 - 30 km
A2	615 - 645	15.9	Temperature 30 - 50 km; Pressure
A3	635 - 665	15.4	Temperature 50 - 90 km, Pressure
A4	820 - 870	11.8	Water ice extinction 0 - 90 km
A5	400 - 500	22.2	Dust extinction 0 - 90 km
A6	3300– 33000	1.65	High altitude hazes and particle size discrimination
B1	290 - 340	31.7	Dust and CO_2 ice extinction 0 - 90 km
B2	220 - 260	41.7	Water vapor 0 - 40 km
B3	231 - 243	42.2	Dust and Water ice extinction 0 - 30 km

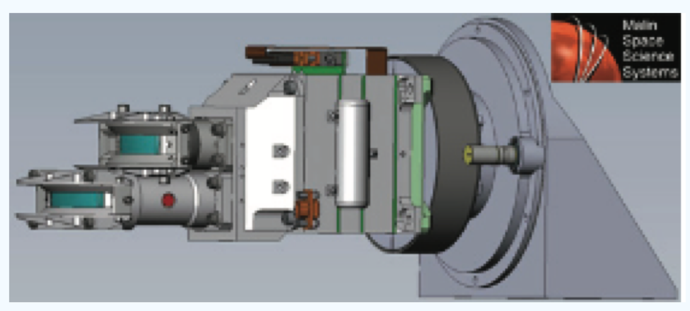
6a. Wide angle camera

A wide-angle camera, such as the MARCI experiment aboard MRO [7, 9] or the MAGIE designed for the ExoMars Trace Gas Orbiter [10] would provide the overall visual context for the winds, water vapor, aerosol, and temperature profiles provided by the other two experiments. On MRO, the MARCI is able to view the dayside of Mars from limb-to-limb on every orbit. With these images, a daily global map, with best resolution of order 1 km, can be made, providing a view of polar weather systems as seen through water-ice clouds as well as cross-equatorial and southern spring/summer dust storms. Having such context would enhance the interpretation of the sub-mm and thermal IR data as well as the ability to adapt observational strategies to impending weather systems, such as dust storms.

Resources for this instrument are estimated to be: Mass: ≤ 5 kg, Power: < 5 W, Data rate: ~75 kbps. TRL = 9 for MSSS.

6b. Wide angle camera figures

A graphic of the selected ExoMars MAGIE wide-angle camera [10].



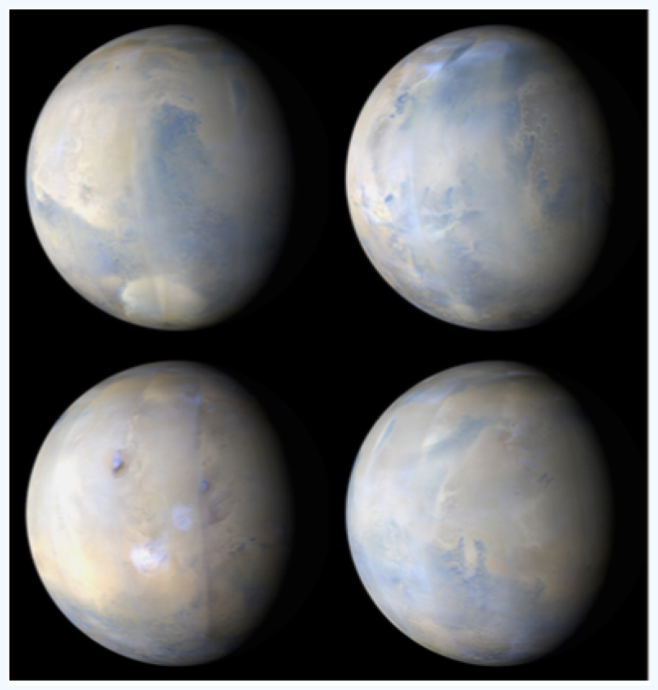


Image mosaics for 4 hemispheres on Mars for Dec. 14, 2007 [7].

References

[1] MEPAG goals document at http://mepag.nasa.gov/reports.cfm. [2] MEPAG NEX-SAG Report (2015; http://mepag.nasa.gov/reports.cfm); [3] D. Kass, pers. comm., 2017; [4] Madeleine et al., 2012. [5] Read et al., (2018), in revision with *Plan. and Sp. Sci.*; [6] McCleese et al. (2007); [7] Bell et al. (2009). [8] Kleinböhl et al., IPM conference 2016.. [9] Malin et al. (2001). [10] Cantor et al. (2011). [11] Tamppari et al. (2014) R&TD annual report. [12] Kleinböhl et al., JGR (2009). [13] Kleinböhl et al., JQSRT (2017).

7. Mission Concept

This instrument payload could fly on a chemical or solar-electric propulsion system. It could also be a subset of a larger payload. It should orbit Mars for at least 1 Mars year, though a multi-Mars year orbiter is highly desired.

A solar electric propulsion option is favored because it would allow the orbit to be changed from sun-synchronous orbit to one that changes in local time over the course of several 10s of sols (e.g., with solar inclination near 70°). Because of our existing baseline of atmospheric temperatures, column abundances of water vapor, and aerosol profiles taken from ~3 p.m. fixed local time orbits, it is desirable to obtain a Mars year of data in a similar orbit and then transition to an orbit that will cycle through local time.

From a previous study [11], either a traditional chemical propulsion system or a solar electric propulsion system could carry the mass of this payload with ample margin on any launch opportunity through 2026. A chemical propulsion system, a "small' spacecraft bus may be challenged in providing the power needed, but solar electric propulsion systems are common now and offer additional power due to the enhanced solar panels. For nighttime (more importantly, eclipse) observations, a single 50-kg Li-ion battery should be ample to continue observations [11]. A mission of this size would be able to launch on a Falcon-9-class vehicle.

Finally, this mission could also carry an Electra radio and could be used to relay surface asset data to back to the Earth, increasing the robustness of the orbital relay asset infrastructure currently at and planned for Mars.

8. Mars Climate Mission Summary

Science Objectives: The primary science objectives of *measuring for the first time global profiles of wind and water vapor,* along with simultaneous temperature and aerosols in order to understand Mars' current climate and weather **directly address the highest priority MEPAG Goal II, Obj. A1, in totality**, by addressing all three high-priority investigations: A1.1 (measure state and variability of lower atmosphere), A1.2 (characterize dust, water vapor, clouds), and A1.3 (measure the forcings that control dynamics and thermal structure).

Mission implementation: This complement of instruments is appropriate for small/medium competed missions, directed missions, or as part of larger competed missions.

Timeframe for mission: This mission could easily flown in the 2023-2032 decade, assuming funds available, as the techniques are high TRL. Advantages to flying this mission in the next decade include (1) ensuring continuity with the current history of Mars atmospheric measurements, enhancing the combined science return of all measurements, and (2) enhancing the programmatic goals (atmospheric support of other missions and landed asset data return) through the MSR mission timeframe. It could also be flown after the MSR mission, if funds are unavailable until then.

MEPAG studies: This mission could benefit from a study (Team-X study or more in-depth) to define the overall implementation: spacecraft bus, propulsion, launch vehicle, mission design, mission mass, power, and data rate/volumes needs, and Phase A-E costs, as a function of launch date.

This Mars Climate Mission would achieve very high-priority [1, 2] and long-outstanding science measurements, with a payload that is overall high-TRL, low-risk, with modest mass, power, and data rate needs, and would enhance the programmatic infrastructure at Mars. It could be accommodated with a variety of spacecraft bus and propulsion designs, and could be launched on a smaller-class rocket. Using solar electric propulsion increases the value of this mission by allowing multiple orbits within one mission and increases the robustness with respect to power.

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