Planetary Decadal Survey White Paper
on

The Martian Atmospheric Gas Evolution (MAGE) Experiment:
an Off-Axis Integrated Cavity-enhanced Output Spectrometer
(OA-ICOS) enabling high-frequency near-surface trace gas
measurements on Mars

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1. Trace gas observations hint at enigmatic chemical processes on Mars.

Two decades of observing methane on Mars¹⁻⁷ have generated data indicative of a dynamic, geochemical system characterized by a profile similar to the release of methane from seeps on Earth^{25,27} producing both (1) distinct pulses known as plumes separated by (2) slow background seepage. The plumes may locally increase CH₄ concentration to as high as 45 ppbv¹ but are geographically and temporally constrained, declining to background levels within days to months. These observations demonstrate a lack of understanding of fundamental aspects of the Martian methane cycle, such as the identification of methane sources and sinks. **Measurements of methane on Mars have raised significant questions into the geochemical processes that could account for the observations, underscoring a pressing need for additional data in the form of near-surface, high-frequency observations.** In this context, we define “high-frequency atmospheric gas measurements” as sub-diurnal and ideally hourly, striking a balance between capability and cadence. Contextual measurements would include meteorological data collected at a rate consistent with eddy flux capabilities in planetary boundary layers (~10 Hz). This white paper will describe mission scenarios enabling high frequency measurements of methane in addition to other trace atmospheric gas concentrations such as O₂, CO, O₃, and ethane. Methane in the Martian atmosphere has an atmospheric lifetime of ~300 years, implying that the observed methane has been recently generated or recently released. On Earth, most methane in the atmosphere is biogenic; as such, understanding the mechanisms of methane cycling on Mars has significant implications for the potential of extant life in the Martian subsurface.

The subsurface represents the largest, longest lived, putatively habitable environment on Mars⁹⁻¹⁴. On Earth, it is estimated that the majority of all bacterial and archaeal biomass is in the subsurface¹⁵ with a significant fraction sustained through chemoautotrophic metabolisms decoupled from organic photosynthate¹¹. Many of these microbial communities fix CO₂ and exploit redox gradients for energy, metabolizing trace atmospheric gases including H₂, CO, and CH₄¹¹. H₂ and CH₄ are essential energy sources capable of supporting potential chemotrophic metabolisms in the Martian subsurface¹⁶. On Mars, as on Earth, H₂ may be produced through 1) cataclastic processes that can also generate ozone¹⁷⁻¹⁹, 2) serpentinization^{20,21}, and/or 3) radiolysis²². The higher porosity at a given depth on Mars as compared to Earth²²⁻²⁴ suggests that H₂ flux in the Martian subsurface via radiolytic H₂ production may be greater than on Earth.

While methane can be produced on Mars abiotically through thermogenesis of abiotic organics delivered by meteorites and IDPs²⁵ and by Fischer-Tropsch-type reactions (CO₂ hydrogenation, using H₂ produced by serpentinization or radiolysis²⁵⁻²⁸), on Earth, significant amounts of methane are also produced through microbial reduction of CO₂. Determining the biogenicity of CH₄ is non-trivial and requires a correlated multi-analytical approach including determination of carbon isotopes and concentrations of associated gasses, such as ethane and propane^{26,29}. In terrestrial systems, biogenic CH₄ is enriched in ¹²C relative to ¹³C. However, overlapping $\delta^{13}\text{C}$ values can be obtained through abiotic processes²⁶. Further, the interpretation of

Martian CH₄ isotopic fractionation patterns will require measuring stable isotopic signatures of potential carbon reservoirs. Hinrichs et al.³⁰ have shown evidence for *in situ* biogenic ethane and propane production at sufficient H₂ concentrations in deep marine sediments, such that measuring the ratios of these sister hydrocarbons could comprise an additional criteria for biogenicity assessment.

Even in the absence of identifying CH₄ as a definitive biosignature, variable CH₄ in an otherwise oxidized environment demonstrates dynamic geochemical processes capable of sustaining life. In addition to providing a window into putative subsurface (bio)geological processes, high resolution measurements of trace gases at the near-surface will help constrain potential oxidants, such as ozone and other reactive species, that may form from atmosphere-surface interactions and facilitate organic degradation on the surface^{31,32}. High temporal resolution is crucial to constraining the potential for complex organic molecules to be preserved on the surface as many complex organics have a half life of only hours (e.g., glycine has an estimated half life of ~231 +/- 110 hours on the martian surface³⁴). The identification of complex organic molecules in the Murray and Sheepbed mudstones³⁵ of Gale crater suggest localized and heterogeneous preservation conditions.

2. Current spectrometers have a limited capacity for high frequency measurements needed to understand the two processes driving methane in the atmosphere.

Our understanding of the Martian methane cycle is limited by the relative paucity of measurements. With the exception of a large plume observed in 2013 by both the Sample Analysis at Mars Tunable Laser Spectrometer (SAM-TLS) onboard the MSL rover³ and the Planetary Fourier Spectrometer (PFS) onboard Mars Express⁶, no two measurements have overlapped in space, time, and sensitivity. The lack of coordinating measurements is a product of mission specific and technological constraints. Furthermore, it was recently noted that the spectral overlap between ozone and methane may not be resolved by TLS, confounding interpretation of potential background methane species suggesting that TLS-observed methane peaks not also observed by Mars Express may in fact be a spectral artifact of variable ozone concentrations³³.

A background seasonal methane cycle is observed at the sub-ppb level averaging 0.41 ppbv at Gale Crater⁴ likely resulting from a small, constant process of a few kg/sol³⁶ over the 18,400 km² area of the crater – a sufficiently small release that it would be below detection by the ESA ExoMars Trace Gas Orbiter (TGO) ACS and NOMAD instruments⁷. To adequately describe any episodic process, observations of that process must be obtained at a cadence sufficient to profile flux variations. Observing Mars only at dawn and dusk (via orbital limb measurements, e.g. TGO) or in the middle of the afternoon and night (via Sun-synchronous mapping orbits, e.g. MRO, MGS) will miss diurnal effects. An instrument capable of methane measurements with a

high temporal resolution would fill the temporal gaps, addressing large uncertainties in current models (see the companion science white paper, Moores et al., 2020).

There are several new measurements needed to understand the key processes that contribute to the observed levels of methane in the atmosphere. First, all of the plumes measured to date consist of a single temporal point observation of elevated methane as observations are often separated by months precluding a clear interpretation. The ramp-up of a plume or the decay of a plume has never been recorded, challenging theories of methane production and dissipation on Mars. Second, no measurement has been made of the entire diurnal cycle of the background seepage. Moores et al.³⁶ show that strong diurnal variations of a ppbv or more should exist when constant seepage is combined with TGO constraints on methane content in the upper atmosphere. Finally, a measurement of the ^{13}C to ^{12}C isotopic ratio of the methane released during a plume event may help constrain formation processes. Off-Axis Integrated Cavity-enhanced Output Spectroscopy (OA-ICOS), developed by ABB Inc. is capable of accomplishing all three goals.

Here, we propose a small autonomous, stationary, surface trace gas observatory (including the OA-ICOS and context sensors) capable of obtaining high-frequency trace gas measurements at the sub-ppb level with low resource requirements and a form-factor approximating a 6U cubesat that would be compatible with three mission scenarios: (1) Primary payload of a dedicated landed mission (stationary), or an instrument contribution that can be (2) Integrated into a lander, or (3) Rover deployable (stationary or rover-mounted).

3. MAGE OA-ICOS: A small gas analyzer to conduct hourly, sub-ppb measurements of methane on Mars from a landed platform.

The proposed MAGE sensor would be based on ABB's OA-ICOS (Off-Axis Integrated Cavity-enhanced Output Spectroscopy), a robust instrument capable of obtaining frequent, sub-ppb measurements of trace gases that has been deployed terrestrially on aircraft, automobiles, and drones. The sensor is currently being developed for space applications through a grant of the Canadian Space Agency (CSA) Flights and Fieldwork for the Advancement of Science and Technology (FAST).

Though the technique is comparable to Cavity-Ringdown Spectroscopy (CRDS), the OA-ICOS has several advantages that make it uniquely suited for planetary space missions

compared to CRDS. These include a lack of precisely aligned optics, making the instrument highly resistant to vibration (launch and EDL) as well as pressure and temperature changes (100 K difference between day and night on Mars). The electronics back-end is also much simpler than most CRDS setups, allowing for better and quicker calibrations and fewer potential points of failure. The technique also permits a wider dynamic range for the gasses being analyzed, up to 100% of the inlet gas, allowing CO₂ to be investigated at the same time as gases of more than a billion times lower concentration, such as methane and ozone. The instrument works best at low pressures, removing the need to run the cavity below ambient pressure, though there may be advantages to increasing the pressure with a pump. As such, MAGE could serve as a landed, long-term trace atmospheric gas observatory acquiring frequent high-resolution measurements.

This technique can be compared to existing *in situ* spectroscopic techniques at Mars. Whereas the SAM-TLS spectrometer employs a Herriott cell with an effective 0.0168-km path length, OA-ICOS could be configured with an effective path length of up to 100 km, improving sensitivity by 10,000. Notably, OA-ICOS further removes the resource-intensive step employed by the SAM-TLS that requires several hours of pumping over a CO₂ scrubber. As currently designed for commercial use, the drone-mounted OA-ICOS has a mass of 3 kg and could be accommodated within a 6U-sized deployable surface package such as the SAMPLE (Small Atmospheric Mars Payload Landed Element) concept that has been studied by Magellan Aerospace, York University, and the University of Alberta with funding from CSA.

4. Measurement Objectives and Constraints

Table 1: MAGE Observation Parameters			
Species	Cadence	Concentration	Purpose
CH ₄	Hourly	0.2 - 20+ ppbv	To seek new chemistry and to understand abiotic and biological sources and sinks
O ₃	Hourly	< 300 ppbv	To correct methane concentration
CO ₂	Hourly	95%	For calibration & total pressure
CO	Hourly	0.07	To assess carbon-oxygen cycling and atmospheric disequilibrium
O ₂	Hourly	0.2%	To understand the oxidation potential of the martian atmosphere
C ₂ H ₆	Plume	unknown	To help distinguish between biogenic and abiogenic methane and assess broader martian hydrocarbon cycles
¹² CH ₄ / ¹³ CH ₄	Plume	unknown	

To characterize both the plumes and the background/seepage, **it is necessary to acquire high frequency measurements for at least one Mars year**. While the diurnal evolution of the background is somewhat predictable, for a particular seepage rate, there are seasonal variations

that may reveal information on the condition of the subsurface, and will suggest production mechanisms for methane if simple adsorption and diffusion are insufficient to completely explain the data³⁸. For plumes, there is no way to know when these will arise and they can dissipate very quickly. Notably, the NY Times Plume³⁶ disappeared within less than 2 sols. As such, continuous monitoring is the only way to detect these events. It is not clear how frequently such plumes occur. They have been observed in 2003,^{1,3,6,36,39} but given the paucity of data, the absence of evidence for plumes between these dates should not be taken as evidence of their absence. Indeed, a regular measurement campaign at even a monthly timescale has never been attempted, so we do not actually know whether plumes are common or rare. Nevertheless, **longevity would be an asset for any measurement campaign** thereby increasing the probability that a plume would be observed.

Geographically, even a single station is helpful and useful. The single station would help establish the baseline of diurnal and seasonal variations of trace gas concentrations that are necessary for the recognition of ephemeral events, such as plumes. While the background methane concentration appears to have more to do with the subsurface at the landing site than with global chemistry, there remains a great deal to be learned about near surface trace gas chemistry in general. **Being able to compare multiple ground stations, however, would be very powerful.** This would allow differences in subsurface seepage to be quantified and would allow a global picture to be built up from many individual pieces.

Each measurement of methane should be followed by a measurement of ozone. Ozone is a trace gas present in the Martian atmosphere at up to a few hundred ppbv, and is known to have absorptions in the mid-infrared at wavelengths where methane has significant absorption³³. This gas will confound methane measurements unless it is independently measured. Luckily, there are absorption bands near methane that are unique to ozone, allowing ozone to be measured and corrected out of any resulting methane spectrum.

Two other species should be measured in each measurement: oxygen and carbon dioxide. These are respectively the fourth largest and largest components of the Martian atmosphere. Oxygen is important because of the unusual yearly variation⁴⁰. Carbon dioxide is useful for instrument calibration. Since both of these gases are relatively abundant, their measurement would be relatively quick and straightforward with the OA-ICOS.

If the instrument detects that a plume event is in progress ($\text{CH}_4 > 2$ ppbv), additional measurements should be made. **For such a plume, the MAGE surface observatory could automatically increase the cadence to sub-hourly intervals between measurements. Such a plume event could also trigger the measurement of carbon isotopologues of methane along with ethane, a gas that can accompany a release of biogenic methane on Earth.**

5. Complementary Meteorological Data

In addition to the baseline measurements (table 1), accompanying meteorological data, such as wind speed and direction, temperature, and pressure, should be acquired to place the gas concentration measurements in context to evaluate potential theories for emission and dissipation. Some of this equipment is small, light, and relatively simple to include (e.g. temperature and pressure sensors). Relative humidity could also be helpful, given that ozone is correlated in the upper atmosphere with the presence of water vapour and that many biogenic processes depend strongly on the water activity level. UV radiation sensors could additionally provide data on atmospheric opacity while providing insight into radiation capable of dissociating ozone. Ground temperature sensors could provide information on the surface/atmosphere temperature differential which will inform the thermophysical properties of the ground, giving insight into the vigor and magnitude of the diurnal flux of methane adsorbate.

At the level of more complex but even more helpful instruments, a high-frequency sonic anemometer will allow for determination of turbulence eddy diffusion, which will further constrain the transport of the trace gas. Wind speed and direction would give information on how quickly gas is being advected towards or away from the measurement site. Temperature sensors at multiple elevations, or that penetrate a short distance into the subsurface, could provide more diagnostic data on fluxes and thermophysical properties of the atmosphere and near subsurface. Finally, an all-sky camera could help in directly determining atmospheric opacity and observe dust, clouds, or precipitation.

6. Potential mission scenarios and architectures:

Stand alone station/network or integrated lander/rover instrument

The MAGE system could be deployed in several configurations. One potential application would consider the OA-ICOS as an instrument contribution to a lander or rover mission to Mars - either stationary in a lander or deployed by a rover, or rover-mounted. While the rover-mounted configuration would have the potentially confounding effect of changing terrain over which gas sampling would occur, the rate of sampling would make this a less challenging situation than for interpreting the TLS data from MSL³⁶. Furthermore, a rover would allow seepage to be measured at multiple locations using the same instrument, permitting cross-calibration. In the case of the rover, the OA-ICOS would be supported by the other instrument packages on the rover that could provide the meteorological context and enable plume tracing to a plume source as demonstrated by Banfield et al⁴¹.

Alternatively, the OA-ICOS could be deployed as part of a stand-alone weather station at one or more locations with complementary meteorological sensors, power generation, communications, and thermal control systems (collectively the MAGE station). Magellan Aerospace, in partnership with York University and the University of Alberta, completed a CSA-funded concept study for a rover-deployable 6U-sized weather station called SAMPLE (Small Atmospheric Mars Payload Landed Experiment) that could serve as a basis for MAGE. The baseline instruments for SAMPLE included temperature and humidity sensors, a sonic anemometer, and a wide-angle sky camera. Inclusion of the OA-ICOS for MAGE is feasible with modifications to the baseline SAMPLE platform. A potential mission scenario could involve a rover deploying the MAGE station at a suitable location. Gradually, as more missions arrive at Mars, a network could be built up of individual MAGE stations, although even a single station would revolutionize our understanding of the evolution of near surface trace gas concentrations.

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