DISTRIBUTED INSTRUMENTS FOR MARS SURFACE SCIENCE: OPPORTUNITIES AND TECHNOLOGY FEASIBILITY. M.A. Mischna[1] R.C. Anderson[1], S. Bandyopadhyay[1], E. Brandon[1], A. Goel[1], F. Rossi[1], J. Vander Hook[1], M. Villarreal[1], and M. Wronkiewicz[1], Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; michael.a.mischna@jpl.nasa.gov.

Introduction: A distributed instrument (DI) is an instrument designed to collect spatially and temporally correlated data from many networked, geographically distributed point sensors. A DI is more than the sum of its sensors, however. By strategically scheduling measurements across a region to capture data with spatial context, it can provide insight into spatially and temporally correlated phenomena that are impossible to obtain using only rovers or orbiters.

It is generally recognized that DI hold the promise to unlock answers to key questions in Mars science that cannot easily be addressed by point measurements or orbiters alone, including how solar tides and pressure waves propagate through the martian atmosphere, from where trace gas emissions originate, and the structure of the martian interior. For some fundamental science questions, the output received from a DI of modest capability would be significantly more valuable than the output from a single sensor with exceptional capabilities [1-3].

Today, many individual technologies for DI are arguably mature or at a tipping point, thanks to recent advances in miniaturization of sensor technology, distributed sensing, delay-tolerant networking, orbit-based localization, and EDL and swarm guidance. Distributed instruments are routinely used for Earth science (e.g., for earthquake detection and warning), to inform weather forecasts and climate studies, and for detection of industrial methane leaks. Despite this, comparatively few DI designs have emerged in the planetary science community, and fewer still for Mars exploration.

Science Cases for DI at Mars: Some example applications of DI to scientific questions of high importance are shown here. In establishing these sample cases, we considered: 1) the compelling nature of the particular investigation, focusing on topics identified in the most recent Planetary Science Decadal Survey [4]. 2) examples that focus on in situ science. While remote sensing applications of DI (e.g., orbital swarms, interferometers) are plentiful, in situ, surface-based investigations can perhaps best demonstrate the full range of DI applications, and 3) examples that showcase the *unique benefit* of DI; that is, science questions that can only be satisfactorily answered through the collection of multiple, geographically distributed, spatially and temporally correlated measurements.

Localization of seismic events: The InSight mission demonstrated the value of seismic measurements for characterizing the martian interior. While seismic event localization can be performed with a single instrument by carefully measuring arrival times and polarization, the process is highly challenging and requires extremely high-quality data. At least three seismometers are needed to enable triangulation-based localization of seismic events. Given a priori knowledge of seismically active regions [5], a regional DI comprised of sensors working in tandem may provide the greatest benefit.

Trace gas detection: A high-priority scientific goal identified by the Mars Exploration Program Analysis Group is to "determine if Mars ever supported, or still supports, life" [2] through surface and subsurface smart sensor systems that can localize the origin of atmospheric methane sources and help determine whether Mars is still active (e.g., heat energy generated by magma and tectonism) and contains groundwater reservoirs. Coincident measurements taken regionally around sites of interest can, with modeling support (e.g., [6]) localize sources of atmospheric methane.

Global climate and weather: Understanding atmospheric circulation is a key scientific priority for Mars, due to its relevance not only to fundamental questions of planetary formation and evolution, but also to entry, descent, and landing and, eventually, to human exploration. Measurements to date have either provided *global* coverage from remote sensing (i.e., orbital) assets, with low temporal resolution (typically 2x per day), or *hyperlocal* measurements taken from rovers and landers, with low spatial resolution. A suite of integrated sensors across a wide range of surface locations (Fig. 1) would enable a proper visualization of the global motions of the atmosphere, observing the entire planet simultaneously at multiple distributed locations.

Enabling Technologies: Realizing the benefits of DI poses novel technology challenges that are not typically faced by monolithic instruments and missions. Examples of technologies uniquely relevant to DI include:

- Localization and synchronization: how to determine the spatial and temporal correlation of sensor measurements
- Communications: how to relay data from the sensors back to Earth, and how sensors can trigger each other

- Adaptive sampling and instrument autonomy: how to intelligently trigger the sensors and compress data so as to fit within tight power and bandwidth constraints, and
- Coordinated sensor placement: how to efficiently achieve the desired spatial distribution of the sensors on the surface.

In addition, individual sensors of a DI would likely be required to fit in a small envelope for size, weight, and power (SWaP), to allow for efficient deployment of the instrument. Accordingly, the design of DI is likely to be constrained by technical challenges that affect small instruments, namely:

- On-board computation and storage: what hardware is available to process and store data on board
- Power: how to ensure the sensors can operate for the entirety of the required mission, and
- Thermal control: how to satisfy the thermal constraints of the sensors and ancillary technologies

The majority of required technologies are mature and ready for incorporation in a DI architecture (Fig. 2); however, additional focused research and development are needed [7] in three key areas:

- EDL and sensor placement techniques that can ensure global access to the martian surface. Global distribution requires either multiple launches or independent EDL platforms for each sensor node because strategies for dispersing during EDL or after landing are not yet tenable
- Compact and long-lasting power solutions for individual sensing units, especially for high latitudes. To maintain low cost and increase mission life, a combination of solar arrays and rechargeable energy storage likely offers the best approach, though it depends on many factors, including the nature of the electrical loads (average and peak power levels), location, and environment.
- Instrument autonomy, especially data compression for distributed seismology and active sampling techniques to curtail power requirements for all classes of DI. Onboard science autonomy software is a way to mitigate demands on the sensor platform by applying, for example, content-based compression and prioritization to return the most scientifically valuable data to Earth

Conclusions: Distributed instruments are useful for investigating a range of scientific questions on Mars, including seismic activity, climate and trace gas localization. While some focused technology improvement is needed in areas of sensor deployment, power solutions and instrument autonomy, off-the-shelf sensor technology combined with a microlander framework could support small, affordable DI missions of ~3-4 nodes for well within the cost cap of a low-cost mission program.

References: [1] Beaty, D.W. (2012) *MEPAG final report of the P-SAG*. [2] Banfield, D. et al. (2020) *MEPAG Goals Document*. [3] Barba, N. et al. (2019) *Mission concept engineering assessments to support ICE-SAG*. [4] National Academies of Sciences, Engineering, and Medicine, *Origins, Worlds, and Life*, (2022), 800pp. [5] Stähler, S.C. et al. (2022), *Nat. Astron.*, 6, 1376-1386. [6] Luo, Y. et al. (2021), *Earth & Space Sci.*, 8. [7] Wronkiewicz, M. et al. (2022), *Low-Cost Mars Workshop*, #5049.

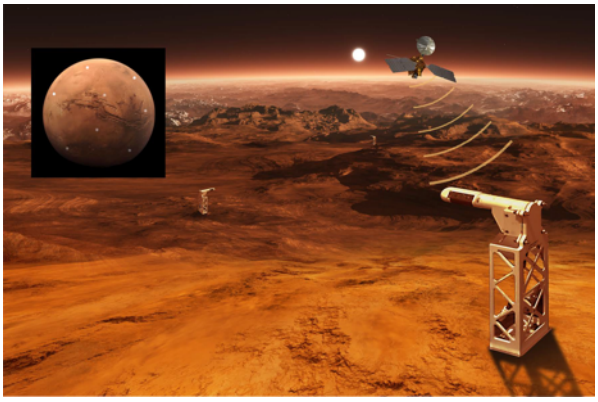

Figure 1: Artist's representation of a notional DI to study martian global climate. A network of ~16 such sensing units is distributed across the martian surface to provide coverage of the entire planet. The DI would allow scientists to study the spatial and temporal correlation of weather and climate patterns.

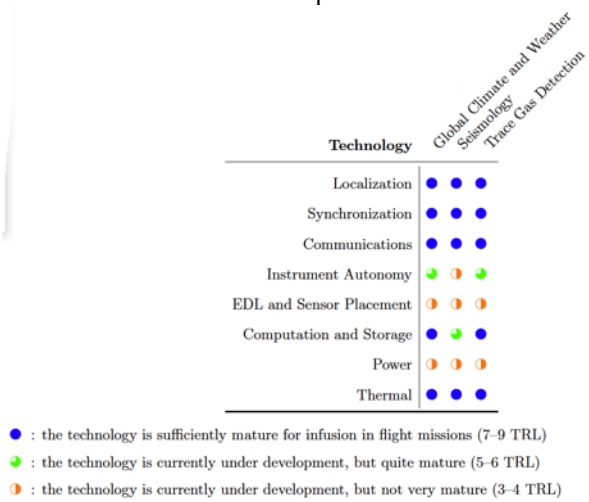

Figure 2: Maturity of enabling technologies for each of the presented science concepts.