Toward Economically Addressing Surface Science Questions on Mars with Distributed Instruments.

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Background and Motivation: Robotic exploration of the solar system has relied heavily on large, single spacecraft missions equipped with many instruments. This has led to many important scientific discoveries, but some scientific questions are difficult to answer with data from a single state-of-the-art rover or orbiter. For example, the localization and analysis of seismic events or characterization of large-scale atmospheric phenomena is hard to perform with monolithic instruments; in contrast, these science questions can be sufficiently addressed with measurements from modest-quality, less-expensive instruments when sampled simultaneously from different spatial locations. Toward this goal, we explore Distributed Instruments (DIs). A DI is a collection of geographically dispersed sensors designed to strategically collect spatially and temporally correlated readings at known locations [1]. DIs are suitable (and in some cases, required) to gather the data needed for investigating dynamic, distributed phenomena. Furthermore, they involve manufacturing multiple copies of a single platform architecture and equipping this platform with off-the-shelf sensors. We explore which aspects of DIs lend themselves to lower-cost Martian surface science and discuss areas where further development is needed.

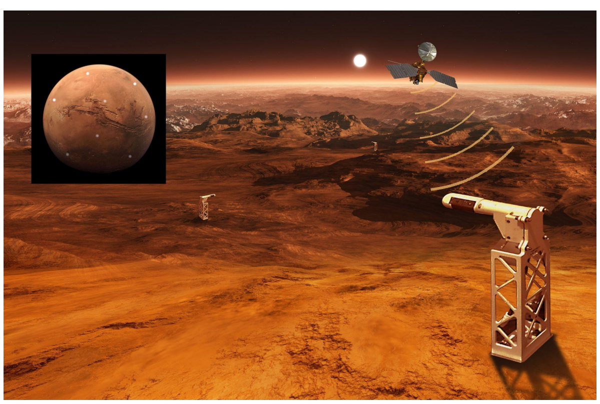

Figure 1. Artist's illustration of a DI to study Mars. Each node in the DI network contains a modular set of instruments to observe atmospheric, seismologic, and/or other phenomena.

Uniquely Addressable Science Questions: DIs are uniquely suited to answer science questions involving large-scale, surface-level phenomena. On Mars, there are at least four such high-priority areas of scientific inquiry. First, investigation into active geological processes is greatly simplified when multiple, distributed measurements are available for the same event. For example, the localization of seismic events (i.e., Marsquakes) is substantially easier when data is collected from multiple locations [1].

Second, cycling of dust, water, and CO_2 remains poorly understood. Climate modeling has been stymied by the absence of distributed, diurnal, atmospheric measurements (e.g., 3D surface wind speeds) [2]. A DI can support modeling and investigation into the Martian climate (e.g., seasonal variations in the atmospheric composition and characterization of transient dust storms) through simultaneous sampling of these dynamic phenomena from multiple locations. Again, important scientific advancements are achievable with relatively inexpensive sensors.

Third, trace gasses (e.g., methane) require measurements from multiple sensors to localize their source. On Earth, methane detection has long relied on arrays of sensors to better understand the shape and dynamic concentration of methane gas plumes. The investigation of Martian methane is important in our search for life as well as an indicator of hydrothermal activity, which could indicate favorable conditions for life [1].

Fourth, investigating the internal composition of Mars through magnetometry can benefit from multiple, landed sensors to measure its internal structure. DIs would provide information about the internal composition of Mars that can answer questions about atmospheric loss. Further, identification of any residual crustal magnetization could help shield future robotic or human landers from radiation.

Key Technologies: *EDL and Sensor Placement.* A significant technological and financial obstacle facing DI platforms is the deployment of the individual sensor platforms. 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. Multiple independent landers in the form of microlanders or ground penetrators are currently the most developed technologies to deliver the nodes of a DI. One such platform, the Small High Impact Energy Landing Device (SHIELD; Figure 2), supports global distribution of DI nodes for about $50 million per lander. Three landers with a transit stage and launch has been projected to cost about $200 million [3]. With SHIELD, each node is packaged into an independent EDL platform and released at slightly different velocities after launch. Over the course of the journey to Mars, the spatial separation between nodes grows, so global coverage is assured by the time the microlenders begin EDL. Miniaturized sensors that can withstand ballistic impact are already in development, but others will require focused investments to improve their robustness to the high impact forces.

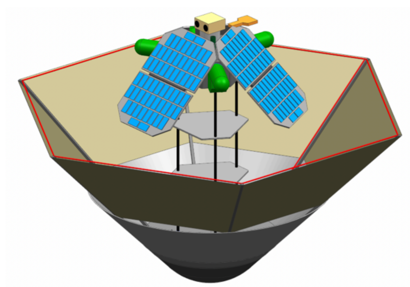

Figure 2. Ballistic SHIELD microlander concept capable of carrying up to 10 kg payload [3].

Power. Compact and long-life power sources are critical for the successful implementation of DIs. Selection of an appropriate power source depends on many factors, including the nature of the electrical loads (i.e., average and peak power levels), its location (i.e., latitude), and the environment of the instrument (i.e., time of year). The lowest cost option would feature the use of primary batteries; however, this approach would practically limit mission life to several months at most. To maintain low cost and increase mission life, a combination of solar arrays and rechargeable energy storage (secondary batteries and/or supercapacitors) offer the best approach. Selection of this option must be traded against other power technologies, based on the peak power needs and total energy required each day [1]. These are impacted by the sun angle and the amount of electrical energy required for heaters. Small radioisotope thermoelectric generators (RTGs) that utilize one or more (1 W_{th}) radioisotope heating units (RHUs) to provide both thermal and electrical power are another alternative, especially where access to adequate solar energy is limited and temperatures are low. However, the use of this technology increases the cost of each node in the DI. These sources would also require on-board energy storage to support peak power requirements, trickle charged by the small RTGs.

Science Autonomy. DIs can leverage onboard science autonomy software as a way to mitigate demands on the sensor platform. For example, content-based compression and prioritization are two related methods to ensure the most scientifically valuable data is sent back to Earth when the full raw data record is too large to transmitted. These methods ensure that data for compelling events (e.g., large magnitude Marsquakes) are fully captured while aggressively condensing or deprioritizing data from less interesting components of the data record. Adaptive sampling is a separate method to reduce power consumption by intelligently regulating data collection rates across the DI network. For example, a DI may operate with low-frequency sampling by default. However, after a sentinel sensor identifies a valuable phenomenon or anomaly (e.g., a growing dust storm), it can trigger the rest of the network to increase data sampling. Reducing data transmission and power spent collecting that data will lower mission costs by reducing demands on energy generation and communication hardware.

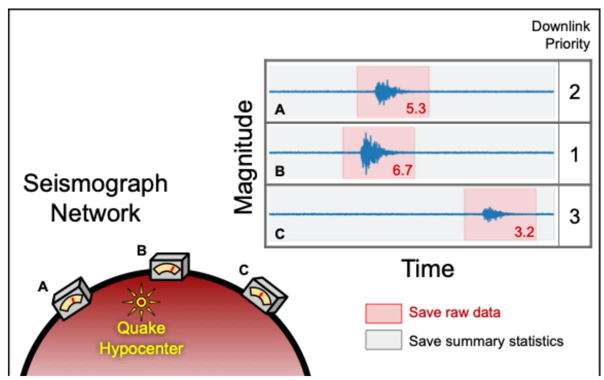

Figure 3. Instrument autonomy for a seismograph network. Multiple DI nodes record activity from a Marsquake. The phenomenon is identified by onboard autonomy (red boxes) and raw data is prioritized for downlink according to magnitude (right of example traces). Quiescent data is summarized with simple statistics to reduce transmitted data and save power.

Conclusions: DIs are valuable for investigating seismic activity, climate, magnetosphere, and trace gases on Mars. While some focused technology improvement is needed (especially deployment of sensor nodes), off-the-shelf sensor technology combined with a microlender concept could support a small DI mission (3-4 nodes) for under $300 million.

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References: [1] A. Goel, et al. (2021) *Planetary Science and Astrobiology Decadal Survey, 53(4),* e-id 156. [2] C. Newman, et al. (2020) *ESSOA.* [3] N. Barba, et al. (2020) *LPI*, #2326, p. 2874.