GEOPHYSICS AND METEOROLOGY FROM A SINGLE STATION ON MARS.

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Introduction: It is well known that multiple landers making simultaneous measurements (i.e., a network mission) are required to fully address the scientific goals of exploring the interior and lower atmosphere dynamics of Mars [e.g., 1]. Such missions have proven extremely costly, and so measurements constraining the structure and processes of the deep interior, shallow subsurface, and atmospheric boundary layer are as yet virtually nonexistent. It is less well appreciated that a single station on the surface of Mars can provide groundbreaking measurements resulting in a significant leap in our understanding of these unexplored areas. Such a mission would use analysis techniques specific to a single station to provide strong constraints on crustal thickness, mantle structure, core size, heat flow, near-subsurface structure and atmospheric processes, providing our first real look beneath the surface of Mars and a comprehensive understanding of the dynamic atmospheric boundary layer.

GEMS: As an example of such a mission, we will describe the Geophysical and Environmental Monitoring Station (GEMS), a low-cost mission concept that was developed as a Mars Scout mission proposal. The key aspects of this mission are its lifetime (which must last for at least a full Mars year) and payload, which consists of the following:

Seismometer. A very broad band (10 µHz to 100 Hz) instrument system with high sensitivity (better than 10^{-9}m/s^2 from 0.001–10 Hz) is required to provide the necessary data quality [2]. A wide variety of analysis techniques have been developed for extracting information about the properties of the Earth's interior and about seismic events themselves. The collection of a high-quality broad-band seismic data set for Mars will provide an invaluable resource for the seismological community to apply various current and future techniques to learn more about Mars. Here we describe several basic approaches to determining the seismicity, crustal structure and deep interior structure.

Distribution of seismicity can be determined by monitoring the body wave frequency band (~0.1-2.5 Hz) for seismic events. The approximate epicentral distance is derived from differential P-S travel times on the vertical record. The initial errors will be ~10%, improving as interior models are refined. The azimuth is measured using the horizontal components, yielding an error of <15%.

Several independent methods can be used to determine crustal structure. The receiver method (using body wave mode conversions at the base of the crust) was successfully applied to the Moon [3]. For the Apollo data a relative error of 10% was achieved on the differential travel time. A second method uses the group velocity dispersion of surface waves at lower frequencies (10-100 mHz) from relatively large events. Such dispersion curves are very sensitive to the crustal thickness. Finally, one can use natural impacts. Calculations suggest that >10 seismically detectable impacts per year should occur. Seismic data will provide an approximate azimuth and range of the events, which might be later improved by differential imaging of the surface with high-resolution orbital imaging [4]. This method, with its precise source locations, could provide data comparable to a controlled, active seismic experiment. The combination of these three methods should lead to a determination of the crustal thickness with a relative error of ~10%.

For a single station, the most effective techniques for studying deep structure utilize normal mode frequencies. Normal mode peaks from 5-20 mHz (the frequency range sensitive to mantle structure) can be identified for a detection noise level of 10^{-9}m/s^2/Hz$^{1/2}$ [5,6]. This can be accomplished by single-record analysis of a large quake of moment ≥10^{18}Nm (equivalent m_b~6) or by stacking multiple quakes with an equivalent cumulative moment.

Seismic data may be able to constrain core size through the measurement of the solid tide amplitude [7,8]. This measurement is limited by the temperature noise (~0.5 K rms in a bandwidth of 1 mHz around the Phobos tide [8]) and would probably require stacking the time series over a period of order a year. Presently achievable noise performance would yield a core radius determination error of ~60 km.

Precision Tracking. Two-way X-band tracking between the lander and Earth can be used to infer interior structure from its effect on variations in the orientation of Mars with respect to inertial space. The precession, nutation, and polar motion of Mars result from the interaction of the interior mass distribution with the gravity of the Sun. A factor of 10 improvement in knowledge of core size should be possible. This improvement results from the increased total time span since Viking, a longer contiguous time span (1 Mars year vs. 90 sols for MPF) and better data accuracy (particularly with respect to Viking). Tracking for more than 1/2 Mars year is required in order to resolve annual and semiannual periodic nutation and polar motion signatures.

Heat Flow Probe. The GEMS concept uses a version of the HP^3 penetrating mole system developed for ExoMars and BepiColombo [9]. This system can penetrate to 3-4 meters in unconsolidated regolith, trailing an instrumented tether that measures temperatures at 20-cm intervals. Together with a thermal diffusivity determination from active heat pulse decay and diurnal wave analyses, it can provide a thermal gradient measurement accurate to a few mW/m. In addition, the penetrator itself provides information on the mechanical properties of the regolith through which it passes, and can carry additional instrumentation (e.g., densitometer, water detector) to characterize the subsurface.

Heat flow is unlikely to be uniform across Mars. Although Mars is not geologically active enough to produce the large difference measured between continents and ocean basins on Earth, there are other contributions. Crater counts suggest that some areas of Mars may have been active within the last 10s of m.y., suggesting possibly elevated temperatures. Depending on the enrichment of radioactive elements, thicker crust in the southern highlands may produce higher heat flow. Climate cycles are predicted to have a strong near-surface thermal wave signature at high latitudes, but are likely to be small in the equatorial latitude band [11]. Measuring the heat flow at multiple locations would provide an exciting opportunity to study these processes. However, simultaneously measurements at different locations are not necessary. A single measurement would provide an important first sample of the heat flow, which would be sufficient to distinguish between contrasting thermal evolution models.

Ground-Penetrating Radar. GPR can determine the location, orientation, and electromagnetic characteristics of reflectors in the subsurface arising from variations in stratigraphy, structure, and volatile content (e.g., ice, liquid water and gas hydrate). The analysis and interpretation of GPR measurements also yields information on the electrical properties of the subsurface materials which, in turn, provides insight into the composition and processes of formation of the regolith. Terrestrial experience has demonstrated that GPR is particularly well-suited for identifying and quantitatively assessing the distribution of subsurface water.

A problem with a classical monostatic radar operated at a single location stems from the fact that the echo directions are ambiguous, rendering it impossible to retrieve the locations of reflectors. To solve this problem the GEMS GPR uses a system which both detects the returning signals and determines their direction of arrival [12]. This requires a magnetic antenna that can be rotated to provide 3 orthogonal axes, in addition to 4 transmit/receive electric antennas. This configuration can determine the propagation vector of the waves with an accuracy better than 5˚-10˚. With a frequency of 2 MHz, we anticipate penetration to 2-3 km. This frequency is below the ionosphere critical frequency, which will provide a shield against galactic EM noise during the day.

Atmospheric Boundary Layer Package. The near-surface weather and climate on Mars are characterized by large-scale seasonal variations in atmospheric pressure, temperature, and wind velocities. Nighttime temperatures near the surface can fall below the local dew point, causing the formation of ground fogs and surface frost. The episodic regional and global dust storms produce even larger variations in the atmospheric thermal structure and dynamics, and can have long-term consequences for the surface morphology through aeolian erosion and deposition. An improved understanding of the processes responsible for the exchange of heat, mass, and momentum through the planetary boundary layer (PBL) is needed understand these and other aspects of the martian near-surface climate and their consequences for the atmospheric general circulation and surface-atmosphere interactions.

A long-lived lander can accommodate a variety of low-mass/power sensors that can operate simultaneously to characterize the vertical and horizontal energy and mass fluxes through the PBL. The GEMS concept acquires measurements of pressure, temperature structure and dust loading (both near the surface, on an instrumented mast, and higher in the atmosphere using a thermal infrared radiometer and camera), wind and wind shear, humidity, and lower ionosphere height and electron density (using a passive mode of the GPR).

Summary: A single geophysical/meteorological lander would vastly improve our knowledge of the deep interior, near-subsurface, and atmospheric boundary layer, providing essential constraints for models of the thermal, geochemical, and geologic evolution of Mars, especially early in its history. It could also investigate the present day habitability by examining the near-surface (in both directions) thermal, volatile, and meteorological environment, providing vital information on how this environment governs the exchange of volatiles, dust, heat, and momentum between the surface and the atmosphere

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