THE RATIONALE FOR A LONG-LIVED GEOPHYSICAL NETWORK MISSION TO MARS

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Introduction

The signatories of this paper support the development of a set of Mars surface stations (a "network") to study interior geophysical and surface meteorological science. These stations would provide continuous, high frequency measurements not possible from orbit. The science objectives for a Mars geophysical network have been consistently highly recommended by the National Academy for the past 30 years (see National Research Council, 1978, 1988, 1990, 1994, 1996, 1997, 2003a,b, 2008). In particular, the science from this network would directly address many of the previous decadal survey themes (National Research Council, 2003b), along with their attendant measurements:

1. What led to the unique character of our home planet (the past)?
   - Interior and bulk planetary composition
   - Internal structure and evolution
   - Horizontal and vertical variations in internal structure and composition
   - Major heat-loss mechanisms
   - Major characteristics of the iron-rich metallic core
2. What common dynamic processes shape Earth-like planets (the present)?
   - Processes that stabilize climate
   - Processes and rates of surface/atmosphere interaction
   - Active internal processes that shape atmospheres and surfaces
   - Current volcanic and/or tectonic activity
3. What fate awaits Earth's environment and those of the other terrestrial planets (the future)?
   - Consequences of impacting particles and large objects
   - Current flux of impactors

Note that the objectives and methods described in this white paper have significant overlap with a number of other white papers submitted to the Decadal Survey (e.g., Asmar et al., 2009; Edwards et al., 2009; Grimm, 2009; Lillis et al., 2009; MEPAG, 2009a,b; Mischna et al., 2009; Rafkin et al., 2009; Ruedas et al., 2009), illustrating the broad applicability to planetary science.

In the following sections we will outline the scientific rationale for a network mission to Mars, described the measurements required, and summarize key features of its implementation.

The Scientific Value of Mars Interior Investigations from Surface-Based Geophysics

Our fundamental understanding of the interior of the Earth comes from geophysics, geochemistry, and petrology. For geophysics, seismology, together with surface heat flow, magnetic, paleomagnetic and gravity field measurements, and electromagnetic (EM) techniques, have revealed the basic internal layering of the Earth, its thermal structure, its gross compositional stratification, as well as significant lateral variations in these quantities. For example, seismological, magnetic and paleomagnetic measurements revealed the basic components of seafloor spreading and subduction, and seismology alone has mapped the structure of the core, compositional and phase changes in the mantle, three-dimensional velocity anomalies in the mantle related to subsolidus convection, and lateral variations in lithospheric structure. Additionally, seismic information placed strong constraints on Earth's interior temperature distribution and the mechanisms of geodynamo operation. The comprehension of how life developed and evolved on Earth requires knowledge of Earth's thermal and volatile evolution and how mantle and crustal heat transfer, coupled with volatile release, affected habitability at and near the planet's surface. Whereas geophysics can provide information about past processes and states required to reach this understanding, it primarily provides a "snapshot" at one instant in time of how the Earth behaves. This "boundary condition" is a powerful constraint on all models that describe the history of the Earth and attempt to place the evolution of life in this framework, as such models must evolve to this present state.

Mars is a counterpoint to the Earth in how a terrestrial planet evolves. Earth's thermal engine has transferred heat to the surface largely by lithospheric recycling over much of its history, but on Mars there is no evidence in the available record that this process ever occurred (e.g., Pruis and Tanaka, 1995; Sleep and Tanaka, 1995). Over the past ~4 billion years, giant hotspots

(Tharsis and Elysium) have played a significant role in the tectonic and thermal evolution of the planet, and possibly had a causal relationship to an early core dynamo (Golombek and Phillips, 2009), which may, in turn, have been crucial for shielding Mars' early atmosphere from solar wind erosion (Fang et al., 2009). Furthermore, these volcanic complexes released massive amounts of volatiles to the martian atmosphere, which possibly led to clement conditions at times and provided favorable habitability environments (Phillips et al., 2001).

Although the Earth has lost the structures caused by differentiation and early evolution because of vigorous mantle convection, Mars may retain evidence, such as azimuthal and radial compositional differentiation in the crust and mantle. Martian meteorite compositions indicate melting source regions with different compositions that have persisted since the earliest evolution of the planet (Jones, 1986; Borg et al., 1997, 2002), suggesting that mantle convection has been insufficiently vigorous to homogenize the mantle. Further, much of the martian crust dates to the first half billion years of the solar system (Frey et al., 2002). Measurements of the planetary interior may therefore detect structures that still reflect differentiation and early planetary formation processes, making Mars an ideal subject for geophysical investigations aimed at understanding planetary accretion and early evolution. Accretion without initial melting, however, may produce earlier, more vigorous convection, which would have eliminated azimuthal compositional variations (Schubert and Spohn, 1990).

Planetary interiors not only record evidence of conditions of planetary accretion and differentiation, they exert significant control on surface environments. The structure of a planetary interior and its dynamics control heat transfer within a planet through advected mantle material, heat conducted through the lithosphere, and volcanism. Volcanism in particular controls the timing of volatile release, and influences the availability of water and carbon. The existence and strength of any planetary magnetic field depends in part upon the size and state of the core.

The crust of a planet is generally thought to form initially through fractionation of an early magma ocean, with later addition through partial melting of the mantle and resulting volcanism. Thus the volume (thickness) and structure of the crust places strong constraints on the depth and evolution of the putative martian magma ocean and, by extension, planetary magma oceans in general. Currently we do not know the volume of Mars' crust to within a factor of two. Orbital data allows the calculations of variations of crustal thickness (Neumann et al., 2004), but models generally must assume a mean thickness and uniform density for lack of any constraints.

Knowledge of the state of Mars' core and its size is important for understanding the planet's evolution. The thermal evolution of a terrestrial planet can be deduced from the dynamics of its mantle and core. The evolution of a planet and the possibility of dynamo magnetic field generation in its core are highly dependent on the planet's ability to develop convection in the core and in the mantle. In particular, a core magneto-dynamo is related either to a high thermal gradient in the liquid core (thermally driven dynamo) or to the growth of a solid inner core (chemically driven dynamo), or both (Longhi et al., 1992; Dehant et al., 2007, 2009; Breuer et al., 2007). The state of the core depends on the percentage of light elements in the core and on the core temperature, which is related to the heat transport in the mantle (Stevenson, 2001; Breuer and Spohn, 2003, 2006; Schumacher and Breuer, 2006). Thus the present size and state of the core has important implications for our understanding of the evolution and present state of Mars (Dehant et al., 2007, 2009; Stevenson, 2001; Breuer et al., 1997; Spohn et al., 2001; Van Thienen et al., 2007), yet the value of its radius is uncertain to ±10% and it is unclear whether it is solid, liquid or both.

Mantle dynamics plays a key role in shaping the geology of the surface through volcanism and tectonics (Van Thienen et al., 2007). The radius of the core has implications for possible mantle convection scenarios and in particular for the presence of a perovskite phase transition at the bottom of the mantle, which enables global plume-like features to exist and persist over time (Spohn et al., 1998). Such strong, long-standing mantle plumes arising from the core-mantle boundary may explain the long-term volcanic activity in the Tharsis area. Nevertheless, their existence during the last billion years is uncertain. An alternative scenario is that the thermal insulation by locally thickened crust, which has a lower thermal conductivity and is enriched in radioactive elements in comparison to the mantle, leads to significant lateral temperature variations in the upper mantle that are sufficient to generate partial melt even today (Schumacher and Breuer, 2006). We note that the tidal Q of Mars is ~80 (Smith and Born, 1976), substantially less than that of the Earth's mantle (~200), despite it being smaller and presumably cooler than the Earth.

A geophysical "snapshot" of Mars should reveal at a minimum the basic radial compositional structure: dimensions and properties of the crust, the upper and lower mantle, and the solid and/or liquid core. It should also place strong constraints on the radial thermal structure. Studies undertaken during the past decade have developed joint inversion strategies using multiple data sets (e.g., geodetic, seismic and EM; Verhoeven et al., 2005). These methods have been successfully applied to recover the temperature, mineralogy, and iron content of the Earth's lower mantle without trade-off between structural parameters (Verhoeven et al., 2009). The compositional structure relates to the bulk composition of the planet and early differentiation and fractionation of the interior, a time when life may have been spawned on Mars. Thermal structure is derived from the radial seismic velocity structure (particularly phase boundaries), heat flow, and EM sounding and provides the "end condition" on thermal evolution scenarios. Whereas much insight can be gained from a few representative measurements, the delineation of lateral variations in mantle thermal structure derived from a geophysical network with an adequate distribution of stations is necessary to gain full appreciation of heat transfer processes. It is very likely that there remain strong thermal anomalies in the mantle and spatial variations in lithospheric thickness from hot spot processes. In fact without this lateral information the average radial geophysical properties may not be well determined (Kiefer and Li, 2009).

The four primary methods for geophysically probing a planet's interior from its surface are seismology, heat flow, EM sounding, and precision tracking (for rotation measurements), with seismology being by far the most powerful of these. Each is discussed in more detail below.

Seismology

Seismology has provided detailed interior models for both the Earth (with dense networks) and on the Moon (with a sparse network), the latter ranging from simple spherical models (Nakamura, 1983; Gagnepain-Beyneix et al., 2006) to more complex models dealing with the lateral variations (Chenet et al., 2006; Zhao et al., 2008). The level of martian seismic activity remains unknown because of the high sensitivity to wind and poor coupling to the ground of the deck-mounted Viking seismometer (Goins and Lazarewicz, 1979; Nakamura and Anderson, 1979). From models of the thermoelastic cooling of the lithosphere and extrapolation from visible faults (Phillips, 1991; Golombek et al., 1992; Knapmeyer et al., 2006), seismic activity about 100 times higher than that on the Moon has been estimated. A medium activity model (Knapmeyer et al., 2006) generates about 100 quakes/yr with seismic moment greater than 10^{14} Nm (magnitude $M_w = 3.3$) and one per year of seismic moment greater than 10^{17} Nm ($M_w = 5.3$). A concentration of seismicity in the Tharsis bulge is suggested by analysis of visible tectonic faults (Knapmeyer et al., 2006). Impacts are an additional seismic source which may occur at a rate similar to that of the Moon (Davis, 1993). As likely seismic properties of Mars have also been studied quite extensively in the last two decades (Lognonné et al., 1996; Sohl and Spohn, 1997; Mocquet, 1999; Gudkova and Zharkov, 2004; Lognonné and Johnson, 2007), rather strong and conservative constraints can be used for estimating the amplitude of seismic waves, leading to two possible levels of seismic instrumentation (see Table). Levels 0 and 1 (L0 and L1) provide two basic specifications in terms of the quality of the seismometer installation.

Level 0	3-axis VBB (0.02 Hz-5 Hz: <10^{-9} ms^{-2}/Hz$^{1/2}$) Z-axis SP (0.1 Hz-50 Hz: < 10^{-8} ms^{-2}/Hz$^{1/2}$)	**Mass:** 4-5 kg (3.5-4 kg for instrument, 0.5-1 kg for deployment); **Deployment:** installed inside the lander
Level 1	3-axis VBB (1 mHz-5 Hz: < 10^{-10} ms^{-2}/Hz$^{1/2}$) Z-axis SP (0.1 Hz-50 Hz: < 10^{-8} ms^{-2}/Hz$^{1/2}$)	**Add:** pressure sensor (1 mHz-5 Hz; 10^{-3} Pa/Hz$^{1/2}$), wind/thermal shield**; Additional Mass:** ~2.5 kg + arm mass; **Deployment:** installed directly on the ground

Table: Two levels of seismometer installation. Masses are examples from ExoMars Phase B and include I/F, and maturity margins. VBB–very broad band, SP–short period, Z–vertical. Level 0 corresponds to a medium-noise installation and Level 1 represents a better installation with ultra-low-noise instruments.

Seismic network requirements

In order to fully reach their scientific goals, seismic investigations will require a network of at least four L1 stations: three with a spacing of about 3000 km (~50°), and an antipodal station capable of detecting seismic waves traveling through the core (e.g., PKP) from an event simultaneously detected by the others. Such a network may locate, through travel-time analysis, more than 80 globally detectable quakes per (Earth) year and will be robust to unexpectedly high mantle attenuation or low seismic activity. With four or more landers, details of the internal structure, such as the dichotomy or other large unit differences, mantle discontinuities and anisotropy, may be characterized. A less effective L0 network might expect to locate about 20 quakes per year and must therefore last for at least one martian year to be of significant value.

Although less certain, determination of internal structure is also possible with fewer stations under certain assumptions, especially if they are provided with highest quality instruments with superior SNR (e.g., L1). Two landers, as the first step of a seismic network, may also provide key information for selecting the landing sites for subsequent seismic stations rather than depending on a priori information based on remote sensing data. With data from two seismic stations true seismic events are readily distinguishable from local noise. If both are located near a seismically active region (e.g., Tharsis), they may detect a sufficient number of local, shallow quakes to model the crust and upper mantle beneath them. Identifiable impact data would provide similar information. In addition, atmospherically-generated seismicity recorded with two L1 instruments could provide mean phase velocities of surface waves (and thus crustal and upper mantle structure) using cross-correlation techniques (Shapiro and Campillo, 2004).

Even a single L1 station can return certain important information, such as martian seismicity and its geographical distribution, the seismic propagation time through the crust (thus constraining its thickness) and possible large-scale stratification with a use of receiver functions. In addition, the core state and radius can be derived from solid tide measurements (Van Hoolst et al., 2003). If operated for one martian year or longer, such a station could statistically be expected to detect a large quake ($M \geq 10^{17}$ Nm), which would allow recording of planetary normal modes, whose frequencies give direct information about global structure. It may also detect reflected core phases, and possibly normal modes from the atmospherically excited seismic hum (Kobayashi and Nishida, 1998), although identification of such signals may be problematic. Thus, such a station could provide preliminary interior models of the planet far better constrained than present theoretical models.

An incremental network deployment starting with one or two long-lived stations could therefore provide a path for enhanced scientific return. Collaboration among space agencies, exemplified by the International Lunar Network (ILN) effort, may be crucial for deploying an ambitious International Mars Network, as each additional station will significantly improve the quality of seismic data interpretation and considerably increase the total science return.

Heat Flow

Planetary heat flow is a fundamental parameter characterizing the thermal state of a planet. The overall thermal and chemical evolution of planets are fundamental processes influenced by heat flow, and tens of thousands of terrestrial measurements have been made to constrain the heat flow of the Earth. To date, only two independent measurements have been performed to constrain heat flow on the Moon (Langseth et al., 1976), whereas no measurements have been performed on Mars.

Knowledge of the present day heat flux on Mars would elucidate the working of the planetary heat engine and provide essential boundary conditions for models of the martian thermal evolution. This would enable us to discriminate between different evolutionary models, each of which has distinct predictions for when the dynamo was active. A determination of the average heat flow would also provide important constraints on the abundance of radioactive isotopes in the martian interior, which in turn places limits on the major element chemistry. By measuring the mantle contribution to the heat flow in regions of thin crust (e.g., the Hellas basin) questions concerning the partitioning of heat producing elements between crust and mantle and the processes of planetary differentiation could also be addressed.

The thermal gradient from heat flow determines the depths at which liquid water is stable beneath the surface and thus bears directly on this critical habitability parameter (Schulze-Makuch and Irwin, 2008). Furthermore, geothermal energy – i.e., heat flow – is the most important energy source in the martian subsurface today and knowledge of the planetary heat flow would directly constrain estimates of the current biological potential of Mars.

To measure heat flow, the thermal conductivity and thermal gradient in the regolith need to be determined. This is achieved by emplacing temperature sensors and heaters in the subsurface. Thermal conductivity is then determined by active heating experiments or by analysis of the decay of the annual temperature wave with depth. Measurement uncertainties for the conductivity and gradient measurements should each be <10%, resulting in an uncertainty of 15% for the heat flow, comparable to the uncertainty reported for lunar measurements (Langseth et al., 1976). To achieve this accuracy, temperature sensors need to be calibrated to within 0.1 K.

The heat flow from the interior is expected to be uniform over large provinces on the martian surface and much would be learned from measurements at a limited number of selected sites. These would ideally include a representative highland and lowland site, a measurement in the volcanically active Tharsis province and a determination of the mantle heat flow from a measurement in the Hellas basin. Sites must be chosen carefully to avoid overt local influences from topography, slope changes, crater margins and similar heterogeneities.

Precision Tracking – Geodesy

Precision tracking of the martian surface is performed through radio links between ground stations on the Earth (DSP, DSN, or ESTRACK) and landers on the surface of Mars. The experiment consists of an X-band (or S- or Ka-band) transponder designed to obtain two-way Doppler and/or ranging measurements from the radio link. These Doppler measurements over a long period of time (typically at least one martian year) can be used to obtain Mars' rotation behavior (precession, nutations, and length-of-day variations). More specifically, measuring the relative position of the lander on the surface of Mars with respect to the terrestrial ground stations allows reconstructing Mars' time varying orientation and rotation in space. The ultimate objectives of this experiment are to obtain information on Mars' interior and on the mass redistribution of CO_2 in Mars' atmosphere. Precession (long-term changes in the rotational orientation) and nutations (periodic changes in the rotational orientation) as well as polar motion (motion of the planet with respect to its rotation axis) are determined from this experiment and used to obtain information about Mars' interior. At the same time, measurement of variations in Mars' rotation rate reveals variations of the angular momentum due to seasonal mass transfer between the atmosphere and polar caps (Cazenave and Balmino, 1981; Chao and Rubincam, 1990; Yoder and Standish, 1997; Folkner et al., 1997; Defraigne et al., 2000; Dehant et al., 2006; Van den Acker et al., 2002; Sanchez et al., 2004; Karatekin et al., 2005, 2006a,b; Zuber et al., 2007). A great deal has already been learned from such experiments on Viking and Pathfinder, but better tracking accuracy than Viking (which is now possible) and a longer time span than Pathfinder (which lasted 84 sols) are necessary for significant advances.

Precession measurements will improve the determination of the moment of inertia of the whole planet and thus the radius of the core. For a specific interior composition or range of possible compositions, the core radius is expected to be determined with a precision of a few tens of km (compared to ±150 km currently). A precise measurement of variations in the orientation of Mars' spin axis will also enable an independent (and more precise) determination of the size of the core via the core resonance in the nutation amplitudes. The amplification of this resonance depends on the size, moment of inertia, and flattening of the core. For a large core, the amplification can be very large, ensuring the detection of the free core nutation and determination of the core moment of inertia (Dehant et al., 2000a,b; Defraigne et al., 2003).

A large inner core can also have an effect on the nutations that could be measured by radio tracking. Due to the existence of another resonance (the free inner core nutation), there would be amplification in the prograde band of the nutation frequencies. The main effect on nutation would be the cancellation of the largest prograde semi-annual liquid core nutation (Defraigne et al., 2003; Van Hoolst et al., 2000a,b; Dehant et al., 2003). Failure to detect the amplification of the semi-annual nutation with radioscience in its more precise configuration, together with the confirmation of a liquid outer core from the retrograde nutation band and from the k_2 tidal Love number, could then be interpreted as strong evidence for a large solid inner core.

Electromagnetic Sounding

Electromagnetic (EM) sounding has yielded important insights on the interior structures of the Moon and the Galilean satellites (Sonett, 1982; Khurana et al., 1998; Hood et al., 1999). EM methods are widely used to understand Earth's structure from depths of meters to hundreds of kilometers. Recent work in the latter has focused on the water content and partial melting of the upper mantle and transition zone (Karato, 2006; Yoshino et al., 2006; Toffelmier and Tyburczy, 2007; Kelbert et al., 2009). Objectives for Mars include the temperature and state of the upper mantle, the thicknesses of the lithosphere, crust, and cryosphere, and lateral heterogeneity in any of these properties. EM measurements are therefore complementary to seismology and heat flow in constraining the internal structure and evolution of Mars. Atmospheric and space physics investigations will also naturally follow from characterization of the ambient EM energy.

Time-varying EM fields induce eddy currents in planetary interiors, whose secondary EM fields are detected at or above the surface. These secondary fields shield the deeper interior according to the skin-depth effect, so that EM fields fall to 1/e amplitude over depth δ (km) = $0.5\sqrt{\rho/f}$, where ρ is the resistivity (Ω-m) and f is the frequency (Hz). EM sounding exploits the skin-depth effect by using measurements over a range of frequency to reconstruct resistivity over a range of depth (Wait, 1970). Natural EM signals (magnetospheric pulsations, ionospheric currents, lightning) are used instead of transmitters at the low frequencies necessary to penetrate kilometers to hundreds of kilometers into the Earth. Sources for Mars include direct solar-wind/ionosphere interactions, diurnal heating of the ionosphere, solar-wind/mini-magnetosphere interactions, and possibly lightning. These sources will provide a spectrum from ~10 μHz (1 sol period) to >1 kHz.

Forward modeling of a variety of possible subsurface structures for Mars provides broad mapping of measured frequency to depth of investigation. The cryosphere, comprising the upper few to tens of kilometers, is probably very resistive and hence EM-transparent. Underlying, highly conductive saline groundwater would be a near-ideal EM target. Grimm (2002) showed that the depth to groundwater could be determined from measurements in the range 1 mHz to 1 kHz. A wet crust would partly shield the deeper interior on Mars as on the Earth, but in both cases frequencies of 1-100 μHz penetrate to hundreds of kilometers depth. Higher frequencies (up to 100 mHz) penetrate to these depths if the crust is dry. There appears to be a good match, therefore, between the likely natural EM energy spectrum and the desired investigation depths for the EM science objectives.

The fundamental quantity derived in these experiments is the frequency-dependent EM impedance Z. Two methods are suitable for constructing Z from measurements at the surface of Mars. *Geomagnetic Depth Sounding* (GDS) uses surface arrays of magnetometers to determine Z from the ratio of the vertical magnetic field to the magnitude of the horizontal magnetic-field gradient (Gough and Ingham, 1983). Using this method, frequencies of 10-100 μHz from ionospheric sources can be used to probe the mantle. The *Magnetotelluric method* (MT) uses orthogonal horizontal components of the local electric and magnetic fields to compute Z. Mars MT will likely best apply to higher frequencies (<1 Hz to ~1 kHz) and hence exploit 0.01-1 Hz direct solar-wind/ionosphere interactions (Espley et al., 2006) as well as Schumann resonances (~10-50 Hz) and TM waves (>100 Hz) due to lightning. MT therefore focuses on the relatively shallower crust and cryosphere. Together, GDS and MT can address the EM goals for Mars exploration.

Meteorology

Although meteorological payloads on a seismology-focused, several-lander network mission cannot fully address the global measurements required to meet the highest priority MEPAG Climate Goal and Investigation (Rafkin et al. 2009), they can address important elements of the goal related to the dust, water, and CO_2 cycles, as well as the behavior of trace gases that exchange with the surface. Specifically, a several-lander network mission can characterize the nature of surface-atmosphere interactions, and how they vary in space and time. These interactions can only be determined from surface measurements rather than orbiters, and have yet to be adequately characterized by any previous landed mission. The most important aspect of these interactions is the exchange of heat, momentum, water vapor, and trace species between the surface and atmosphere. Understanding these exchanges requires long-term, carefully calibrated, and systematic measurements of pressure, temperature, 3-D winds, dust, water vapor, trace species concentrations, solar and infrared energy inputs, and the electrical environment. Such measurements, made at sufficiently high cadence and with some vertical discrimination, will yield quantitative estimates of the vertical turbulent fluxes of heat, mass, and momentum, which in turn determine the surface forcing of the general circulation and the sources and sinks for CO_2, H_2O, dust, and trace species of interest (e.g., methane). Depending on how the network is configured, correlation studies can further help characterize the near surface signature of regional and larger-scale weather systems such as slope flows, baroclinic eddies, and thermal tides, especially if further supplemented with contemporaneous measurements from orbit. Thus, a carefully selected meteorological payload implemented into a geophysical network mission can provide fundamental new data about the nature of the martian climate system.

Implementation

The implementation of a Mars network mission is relatively unchallenging (other than the challenges of the Mars landing itself). The class of geophysical mission addressed here has experienced various levels of full project development (e.g., Squyres, 1995; Harri et al., 1999) and has been studied in detail as part of many competitive proposal activities in both Europe and the United States over the past two decades (e.g., Chicarro et al., 1994; Banerdt et al., 1996; Grimm, 2002; Banerdt and Smrekar, 2007; Banerdt, 2009). The implementation strategy options that have been considered are flexible and can be varied to develop the most cost-effective concept to accommodate programmatic needs and still meet the network science objectives. Implementation strategies include those that leverage existing entry, descent and landing (EDL) systems (e.g., 2003 MER or 2007 Phoenix) as means for successfully placing network measurement packages on the surface with minimal cost and technical risk. A four-node network implementation has been studied for launch in 2018 that has a total project cost (RY$, Phase A-D, including launch vehicle) conservatively estimated to be at the mid- to low end of the $1B – $1.5B range, and a single geophysical lander has been proposed with a cost in the Discovery class. Common key characteristics of these mission options include a one-Mars year lifetime, a robust communication link and (for the network studies) four widely dispersed stations. Surface measurement packages that are dispersed with appropriate latitude and longitude separation are enabled either through sequential release of separate ballistic EDL systems on approach to Mars, with small trajectory adjustments between deployment events from the carrier spacecraft, or through independent trajectories from Earth to Mars. Landing altitude and accuracy requirements depend almost exclusively on engineering constraints and do not present navigation or EDL challenges. No technology development is necessary for instruments and engineering systems to land, deploy and operate the network stations. Data relay would be enabled by current and/or anticipated orbital assets at Mars (e.g., 2013 MAVEN or a planned NASA/ESA 2016 Trace Gas and Imaging Orbiter mission) in addition to those orbiters already present at Mars (Odyssey, Mars Express and MRO).

References

All references cited in this document are contained in “Compiled Bibliographic Citations and Acronym Glossary for the Mars-Related White Papers Submitted to the NRC’s Planetary Decadal Survey”, which may be accessed at http://mepag.jpl.nasa.gov/decadal/index.html.