GEMS: A Revolutionary Concept for Planetary and Space Exploration

John Manobianco[1], James Bickford[2], Sean George[2], Kristofer S. J. Pister[3], and Donna M. Manobianco[4]

[1]*ENSCO, Inc., 1980 N. Atlantic Ave, Suite 230, Cocoa Beach, FL 32931*
[2]*Charles Stark Draper Laboratory, 555 Technology Square, Cambridge, MA 02139*
[3]*Dust, Inc., 2560 Ninth St., Suite 218, Berkeley, CA 94710*
[4]*Mano Nanotechnologies, Research and Consulting, 979 Wildwood Dr., Melbourne, FL 32940*
321-783-9735, Ext. 205, manobianco.john@ensco.com

Abstract. A novel observing system known as Global Environmental MEMS Sensors (GEMS) offers the potential to significantly improve the ability to take in situ measurements for a variety of space missions. The GEMS concept features devices with completely integrated sensing, power, and communications with characteristic dimensions of just millimeters. Thousands of these low-cost devices could potentially be deployed together from a spacecraft to enable distributed sensing in planetary and other space environments. The deployment of such probes is analyzed and discussed for various scenarios on Mars that would provide measurements with unprecedented spatial and temporal resolution. The extended coverage provided by the arrays would improve the ability to calibrate remote sensing data while also extending the areas traditionally measured by localized landers. The unique features of such a system could significantly improve the capabilities for planetary and space exploration in the near and far term.

INTRODUCTION

Technological advancements in Micro Electro Mechanical Systems (MEMS) and nanotechnology have inspired a revolutionary observing system known as Global Environmental MEMS Sensors (GEMS). The GEMS concept features an integrated system of MEMS-based airborne probes that will be designed to take in situ measurements with unprecedented spatial and temporal resolution. After completing the airborne portion of their mission, the probes are envisioned to land on the ground and form an array of surface science instruments. Each probe will be self-contained with a power source to provide sensing, computation, and communication functions. The acquired data will be transmitted wirelessly to remote receiving platforms.

In 2002, a number of key engineering issues and enabling technologies affecting the design and development of GEMS were identified as part of a phase I project funded by the NASA Institute for Advanced Concepts (NIAC). The phase II effort commencing in Fall 2003 will study the major feasibility issues in detail to examine the potential performance and cost benefits, and develop a technology roadmap that will help NASA to integrate the concept into future missions and programs. This paper provides details regarding the application of GEMS for planetary and space exploration and highlights progress and plans for the design and development of the system.

KEY ENGINEERING ISSUES AND ENABLING TECHNOLOGIES

The phase I project focused on validating the viability of GEMS, defining the major feasibility issues, and determining the primary enabling technologies that must be addressed for the future design and development of the system. A summary of key issues and enabling technologies is presented in Table 1.

The size, mass, aspect ratio, component geometry, buoyancy control, and aerodynamic design will all determine how long probes remain airborne in planetary atmospheres. Materials science will play a key role to limit probe mass. The intricacy in nature suggests that nanobiotechnology be explored as a possible means from which to create materials suitable for the probes. Nanobiotechnology merges biological systems with nanofabrication. For

CP699, *Space Technology and Applications International Forum–STAIF 2004,* edited by M.S. El-Genk

example, organic cells feature complex "machines" and systems that may guide the design and functionality of micro and nanoscale devices and components (Soong et al., 2000).

TABLE 1. Key Issues and Enabling Technologies Affecting GEMS Design and Development.

Major Feasibility Issues	Primary Enabling Technologies
Probe design	Materials science, nanotechnology, biomimetics
Power	Batteries, micro fuel cells, solar energy
Communication	MEMS-based radio frequency and/or free-space optical systems
Networking	Artificial intelligence (autonomous self-healing networks)
Measurement	MEMS-based sensors
Data collection/management	Artificial intelligence, data mining
Cost	MEMS mass production/packaging, deployment strategies, data collection infrastructure

Buoyancy control is one way to reduce the terminal velocity of probes and keep them suspended for much longer periods of time. Recent work by Chambers et al. (1998) and Chen et al. (1999) demonstrated that hydrogen storage on nanocrystalline materials might be used to regulate buoyancy. Depending on the size and shape of the probes, aerodynamic design could also reduce their ballistic coefficient and terminal velocity. Many examples of such design exist in the natural world, including simple dandelion spokes and threads of balloon spiders, as well as sophisticated evolved forms like the auto-rotating samaras (Walker, 1981).

The probes will be capable of sensing a number of parameters including temperature, moisture, pressure, velocity, chemical/biological compounds, radiation, and dust deposition. Microfabricated devices for sensing temperature, humidity, and pressure are well developed (Kovacs, 1998). There has been a recent surge in microcantilever research for high-sensitivity chemical, biological, and radiation sensing (Wachter et al., 1996; Datskos et al., 2001; Thundat, 2001). In most cases, these existing technologies can be modified for integrated, low-power applications such as GEMS.

In a step towards their ultimate goal of 1-cubic millimeter wireless devices (Warneke et al., 2001), University of California Berkeley researchers integrated a radio transmitter, sensor interface electronics, microprocessor, and memory into a single silicon chip measuring 5 mm^2 (Fig. 1). Single-chip integration of communication, sensing, and computation reduces the cost per device since post fabrication steps can be eliminated. A continued decrease in size and cost through mass production provides ample opportunities for low-cost deployment of large numbers of probes. This scenario is especially suited for planetary and space exploration given that such missions are often constrained by payload mass and cost (Rast et al., 1999). In the three- to five-year timeframe, it would be possible to include thousands of millimeter-scale probes with limited sensing capabilities as payloads on board spacecraft designed for space and planetary exploration.

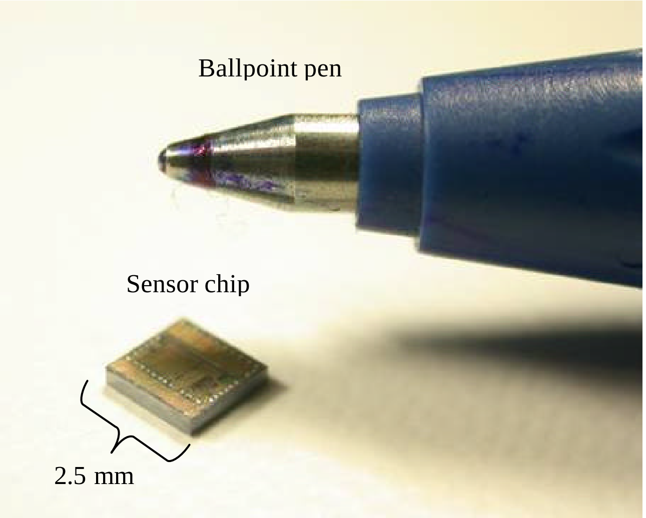


FIGURE 1. Sensor Chip Measuring 2.5 mm x 2 mm for the Latest Generation of Wireless Devices from University of California Berkeley.

APPLICATION FOR PLANETARY EXPLORATION OF MARS

Since the first flyby by Mariner 4 in 1964, Mars has been extensively studied by a variety of robotic spacecraft. Remote observations from orbit, as well as in situ measurements from ground landers, have enabled scientists to decipher the past history of the planet while searching for signs of life. An assessment of the current NASA Mars Exploration Program (MEP) showed that NASA is succeeding in its key program priorities with the philosophy of "Seek, In-situ, Sample" (Space Studies Board, 2003). One of the primary thrusts of the MEP is to identify biological potential by tracing any evidence of current or past water activity. However, an overall understanding of the Martian environment including the atmosphere is needed to increase the probability of success. Since life must be detected with direct in situ measurements, a gross understanding of the planet is needed to narrow the search for a targeted mission. Precursor flights are developing the core knowledge of the planet and identifying the most likely and interesting regions where life might or did exist in the past. Future sample return missions will be targeted at these areas.

Motivation

The direct measurement of "ground truth" by robotic landing craft is essential to the calibration of remote sensing observations from orbit. Localized in situ ground testing is needed to both validate and provide an absolute calibration for the global scale remote sensing results. However, measurements could potentially be affected by a coating of dust that is not representative of the true geological history of a particular area (Greeley et al., 1992). Windblown deposits produce a homogenized compositional average of the environment as samples from one region of the planet are carried to other regions. Observed dust motion and deposition suggests that the dust is globally transported. These aeolian processes play an important role in sculpting the surface of Mars and must be accounted for when analyzing remote sensing data. This mechanism is not completely understood and is one factor that makes it difficult to calibrate the remote sensing data used to study the planet on global and regional scales.

Currently, only three spacecraft have successfully landed on the surface of Mars. The measurements performed at these landing sites provide the critical "ground truth" for calibration of in-orbit remote sensing results. For instance, scientists looking for evidence of water concentrations use neutron and gamma ray measurements to detect the relative abundance of hydrogen at or near the surface (Feldman et al., 2003). The resulting low-resolution values are then normalized by the assumed water content present at the Viking landing sites. However, the calibration is subject to interpretation making it difficult to establish the absolute water content.

Comparatively, ground probes can directly sample for the presence of water and determine the precise location and abundance, albeit over a very limited range. While the orbital spacecraft give near global coverage with relatively low resolution, the high-resolution in situ measurements are limited to within a few meters of the landing site. The disparity between measurement scales produces questions when comparing and calibrating data from the different sources. For instance, are the local measurements different because they represent a local anomaly or do they instead embody an error in the calibration of the remote sensing data?

Experiments performed by ground landers do not suffer from the problem of having to indirectly infer quantities but are limited to a small sampling area surrounding the landing site. Some measurements can also be taken during re-entry and landing, though these are of very short duration. Airplanes have been suggested as a means to extend the range of measurements over Mars (Smith et al., 2000). Airplanes offer the potential to broaden coverage to regional scales at high resolution while directly sampling the atmosphere during flight. However, direct ground sampling remains difficult and the missions are of very short duration. Balloons have been proposed for regional exploration; however they still suffer from similar shortcomings (Zubrin et al., 1998). Balloons also provide limited control over which areas can be sampled since their motion is governed by wind patterns that are not completely understood.

The GEMS concept bridges the gap between the different sensor platform modalities (Figure 2). Probes could be spread over an arbitrarily large area with a seeding density to match mission requirements for spatial and temporal resolution allowing in situ measurements to be taken simultaneously across the full extent of the spatial distribution. The GEMS data can be matched one for one to the different modalities since the coverage and resolution can be arbitrarily chosen by selectively interrogating portions of the distributed array. This overlap in coverage and resolution with other sensor platforms provides a means to directly correlate remote sensing data with properly matched ground results.

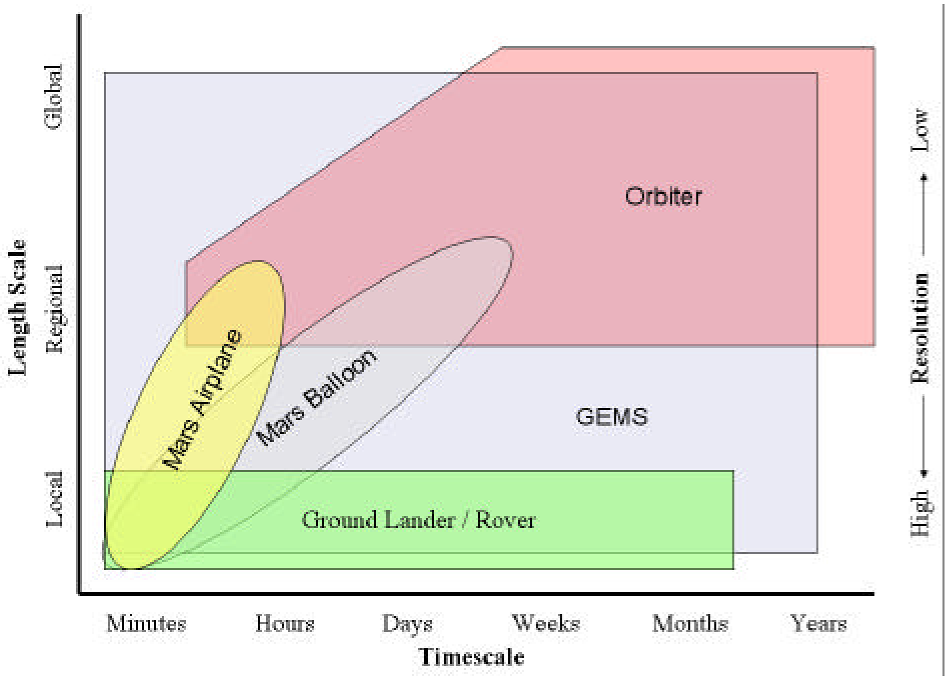


FIGURE 2. Measurement Time and Length Scales for Possible Sensors/Platforms on or Around Mars.

The ability to deploy large numbers of probes over different length scales offers interesting opportunities. For instance, aero-braking maneuvers on the Mars Global Surveyor brought it close enough to the planet to obtain the first magnetic field observations from below the ionosphere. During many of these close passes, the experiment measured crustal magnetic anomalies that were atypical of the global signature and suggestive of localized magnetic phenomena which relate to the early history of the magnetic field, crustal evolution, and composition (Acuna et al., 1998). However, the regions were surveyed over only relatively short periods of the spacecraft's orbit during closest approach. The measurement regions tended to be somewhat randomly situated over a portion of the surface and of a limited spatial resolution. In contrast, GEMS probes could simultaneously measure these locations with unprecedented spatial resolution.

The initial attempts to detect life with the Viking missions did not show any clearly positive signs. However, the sites analyzed during testing were not the regions most likely to contain biological activity, even by the standards of Mars (Klein et al., 1992). For subsequent missions, the lander locations were chosen for their placid terrain to increase the probability of a successful landing. As a result, tests were performed in a very limited region that was relatively uninteresting in the context of biological potential. In comparison, GEMS offers the opportunity to form an array of surface science instruments that would sample in situ like the Viking landers, but with the added ability to do so over vast spatial regions without landing site restrictions. The probes would also provide a large number of in situ pressure, temperature, and wind velocity measurements as they drift through the atmosphere to the ground. These additional atmospheric measurements could significantly increase the landing accuracy of traditional vehicles through improved observations and prediction of air density and wind velocity.

Deployment Scenarios, Dispersion Results, and Discussion

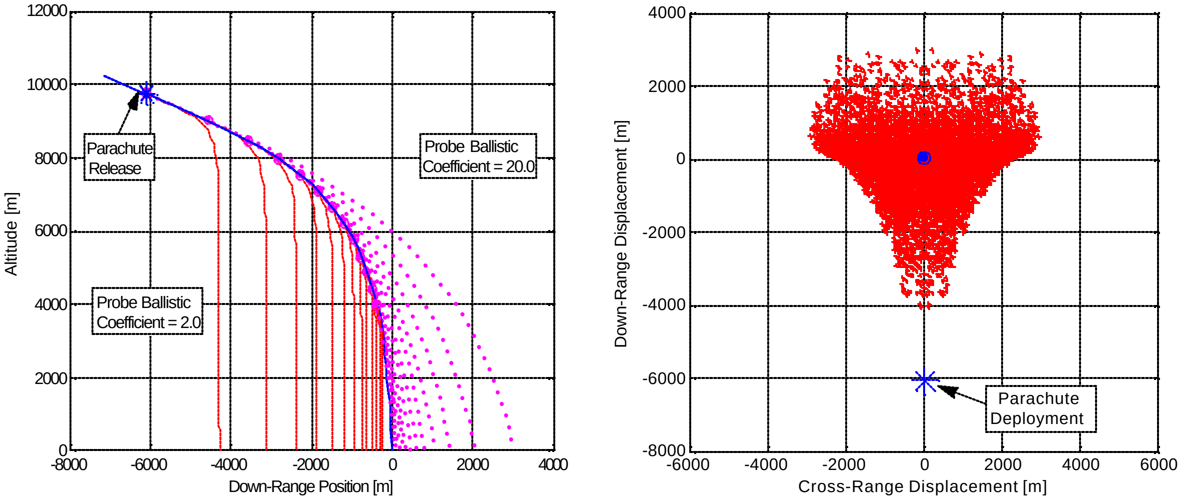
A means to efficiently deploy probes must be devised for the practical use of GEMS. Ideally, deployment systems should be additive and considered a new 'instrument' in current mission concepts. Depending upon the particular mission and quantity to be sensed, coverage can range from local deployment around landers to global dispersion across the planet. Scenarios described here assume that the probes are small idealized particles launched on a ballistic trajectory from a carrier vehicle. Particle motion is governed by a force balance between the gravitational and aerodynamic loads imposed on the falling device. Regan and Anandakrishnan (1993) review the modeling of particle dynamics in atmospheric re-entry scenarios. These equations were used to calculate the dispersion characteristics of the probes in Martian conditions. Multiple scenarios for deployment have been studied to establish the effectiveness of area coverage using different carrier platforms as discussed in the following subsections.

Scenario I: Lander Deployment

The most straightforward deployment method is to launch probes on a ballistic trajectory to disperse them away from the lander (post touchdown) and achieve greater coverage around the landing site. With a range of ballistic coefficients (2 kg $m^{-2} < \beta < 20$ kg m^{-2}) and/or launch velocities ($V_0 < 100$ m s^{-1}), probes can be dispersed up to 1.8 km from the landing site giving a total coverage area of over 10 km^2. This is the simplest scenario and most likely to be implemented in a near term mission since the lander can be used to query and extract the data from the distributed probes.

Using a similar range of probe characteristics, dispersal coverage can be increased by ejecting the probes prior to touchdown. The initial phase of direct re-entry involves a high speed (> 6000 m s^{-1}), ballistic aero-braking stage into the Martian atmosphere. As the lander approaches the surface, the atmospheric density begins to increase, causing a rapid increase in dynamic pressure and a spike in the heating rate seen by the lander. After a substantial decrease in velocity, the heat shield that protects the vehicle during this phase is jettisoned and the main parachute is deployed at speeds around 450 m s^{-1}.

For this initial scenario, probe expulsion was assumed to occur after the deployment of the main parachute, in order to mitigate problems with the high heating rates experienced earlier in the trajectory. Figure 3a shows a sequence of probe releases, parameterized by the probe time-of-release. Two probe designs were examined; a high-drag, “floater” probe with a ballistic coefficient of 2.0 kg m^{-2}, and a low-drag, probe with a ballistic coefficient of 20.0 kg m^{-2}. In order to constrain the impact velocity of the rover, typical lander modules with chute released have been designed with a ballistic coefficient of approximately 10.0 kg m^{-2}. The two probe designs examined in this study were chosen to bracket this value, giving the maximum impact dispersion envelope within reasonable physical constraints.



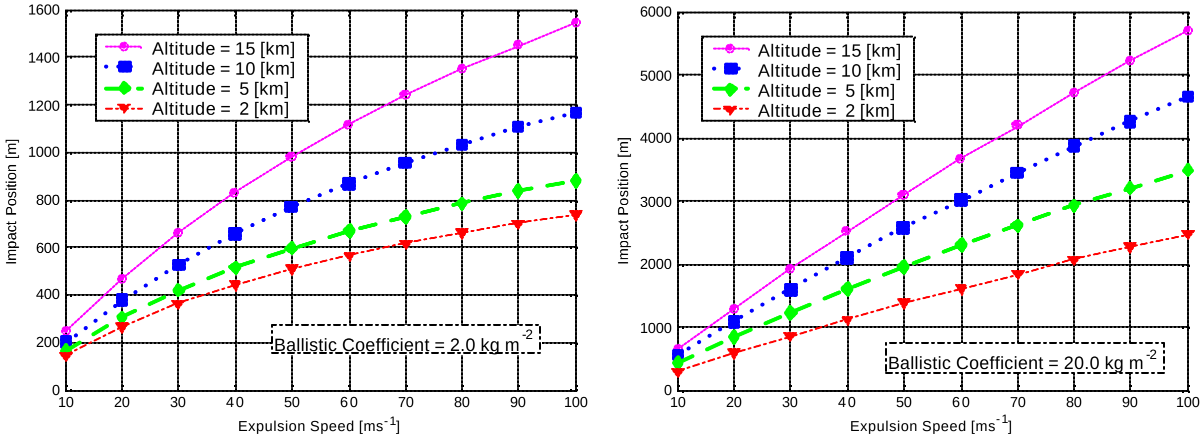
(a) Lateral View of Trajectory. **(b)** Ground Impact for 0-100 m s^{-1} Lateral Ejection Velocity.

FIGURE 3. GEMS Probe Dispersion from Re-entry Vehicle After Heat-Shield Jettison.

A lateral velocity can also be imparted on the probes before leaving the carrier vehicle to increase the dispersion across the ground track. Expulsion velocities from 0-100 m s^{-1} were used to produce the probe cross-track dispersion shown in Figure 3b. This plot was generated by randomly perturbing the probe time-of-release, ballistic coefficient, and expulsion velocity within the limits specified above. Probe dispersions of 7000 meters in the flight-track direction and 6000 meters laterally are possible assuming reasonable release conditions. Changing the launch azimuth of the probes offers the possibility to further increase this value and provide additional ground coverage.

Scenario II: Aerial Deployment

A variety of aerial platforms have been suggested as possible surveyors of Mars (Cutts et al., 1998). GEMS deployment via these platforms is certainly plausible and could effectively increase probe surveillance capabilities. The small size and weight proposed for the probes makes them especially suited for aerial platforms, since the low-density Martian atmosphere restricts the payload carrying capabilities of these aerial devices. Figure 4 shows typical ejection distances for both low-drag and high-drag probes deployed at a variety of release altitudes from generic aerial platforms. Blanket coverage of thousands of square kilometers could be accomplished by spreading the probes over an area extending kilometers away from the flight path of the primary vehicle. Probes deployed along this corridor can remain in situ and continue to take measurements for extended periods of time allowing for simultaneous observations over the entire region covered by the initial flight.



(a) Ballistic Coefficient = 2.0 kg m^{-2}. **(b)** Ballistic Coefficient = 20.0 kg m^{-2}.

FIGURE 4. Probe Dispersion as a Function of Effective Launch Velocity and Initial Altitude.

Scenario III: De-orbiting Deployment

Global-scale dispersion over any portion of the Martian surface can be accomplished by separating the probes from a polar orbiting spacecraft before or just after re-entry. Depending upon the release point and separation velocity, the resulting orbit can be made to intersect the planet at any chosen location. With a range of separation velocities and departure times, seeding the entire planet is theoretically possible. High altitude deployment from a re-entry vehicle or orbiter requires that the individual probes be designed to withstand the heating and forces associated with re-entry and high speed ground impact. Accounting for re-entry heating will likely pose the greatest challenge. A concept where multiple protective canisters deploy the probes after the highest heating rates are encountered might be the simplest option. An ablative coating on the individual probes may also offer a solution and allow for greater dispersion by separating the probes prior to entry. Distributing the probes via a de-orbiting maneuver, rather than during a direct re-entry trajectory, would greatly mitigate the heating issues.

Discussion

The range of ballistic coefficients was chosen to provide information on a variety of possible GEMS applications. Most atmospheric sampling applications will probably require low descent speeds for maximizing airborne residence time, thus making a low ballistic coefficient design preferable. Buoyancy control is possible although the trajectory analysis in this study focused on simple ballistic devices. Ground sampling applications would typically desire lower drag characteristics, since the high descent velocities would minimize wind dispersion while maximizing the dispersion distance if an expulsion device were used. High ground impact speeds would likely not be a difficult design constraint, since high-g instrumentation has already been demonstrated at 60,000g or more

(Anderson et al., 2002). Table 2 summarizes results for options that enable coverage across the full spectrum of deployment footprints needed for potential missions.

TABLE 2. Maximum Coverage Area for Various GEMS Deployment Scenarios.

Deployment Method	Bounded Coverage Footprint
Lander / Rover deployment	3.6 km x 3.6 km
Re-entry dispersal (post chute deployment)	7 km x 6 km
Mars airplane deployment[1]	130 km x 4 km
Balloon deployment[2]	2000 km x 6 km
Multi-point re-entry	Global

[1]Based on Smith et al. (2000); [2]Based on Zubrin et al. (1998)

APPLICATION FOR SPACE EXPLORATION

In addition to using GEMS for exploration of Mars and possibly other planets, the concept is also well suited for in situ exploration and monitoring of the space environment. A massive network of space-based probes is envisioned to contain many more devices than nano- or even pico-satellite constellations (Petschek et al., 1998) and cover a much greater spatial extent. For this application, a constellation of GEMS probes could potentially act as a multi-node, "sun-pointed", observe and report system to provide data on space weather including geomagnetic storms and coronal mass ejections (CME). Once a dangerous space weather event has been detected, signals to a receiving station would likely be interrupted, thus alerting to an impending event. Radiation hardened electronics will likely evolve from advances in micro and nanotechnology.

In the near-Earth environment, CME wreak havoc on satellite operations, navigation, communications, and electric power distribution grids. Space and ground-based assets, and astronauts are subject to potentially dangerous space weather, which can lead to geomagnetic storms. Currently, the Advanced Composition Explorer can provide an advance warning of approximately one hour for such events (David, 2003). As human activity in space increases, it will be more important to provide accurate and timely space weather forecasts. The GEMS system developed for this particular application has the potential to provide longer warning times, and might lead to the creation of new technologies which shield important space assets from possible natural and man-made threats in space.

ADVANCED CAPABILITIES

Initial GEMS applications are likely to sense simple quantities over areas larger than currently possible, to assist in the calibration of in-orbit, global measurements for targeting of future sample/return efforts. Though future applications can utilize a range of sensor types; dust, humidity, temperature, and pressure sensors have the easiest path to integration for systems of this scale. Ultimately, the goal of the MEP is to have humans safely explore the "Red Planet." In order to achieve this goal, a complete understanding of the amount of radiation that reaches the Martian surface will be necessary so that engineers can design space suits and habitats that are conducive for human survival on Mars. It is possible that GEMS probes designed to measure radiation and other "unique chemical characteristics" on the Martian surface could aid NASA in achieving this goal (NASA, 2003a).

More advanced future implementations could use miniature biosensors that would search for life directly. For example, sensors which detect traces of carbon, a known "biomarker", could be included as part of the probe design. Unlike "dry" remote sensing from orbit, in situ measurements are needed to meet the many geochemical and biological goals required to identify the presence of astrobiological activity (Kounaves et al., 2001). By deploying a vast number of probes, the probability of detecting diffuse life increases substantially. The GEMS system has the potential to achieve this goal by monitoring the frozen water-rich polar regions, as well as other geographical areas where liquid water was once stable.

PROGRESS AND PLANS FOR SYSTEM DESIGN/DEVELOPMENT

The key issues and enabling technologies list in Table 1 will be studied in the NIAC phase II project by focusing on physical limitations for measurement and signal detection, scaling as the individual probes become smaller and the number of probes in the network becomes larger, and disciplined engineering optimization of trade-offs. The large number of possible trade-offs based on design characteristics such as sensor accuracy and sampling frequency, deployment scenarios, power consumption, communication range, and other factors constitutes a multi-dimensional parameter space. Because of the high dimensionality and complexity of the parameter matrix, it is not reasonable to attempt a mechanical examination of every possible combination and permutation. Instead, modeling within the framework of simulation-design-test (SDT) cycle will be used extensively as a cost-effective and controlled way to explore the trade-offs, mapping out logical and self-consistent pathways for further detailed exploration. An overall system model of GEMS will be developed following guidelines for systems engineering to merge results from the component SDT cycles. The system model will facilitate understanding how changes in one subsystem will affect other subsystems and the cost-benefit of the system.

A specific avenue for integrating GEMS into future missions is NASA's MEP. NASA and JPL have planned future missions to Mars, including Scout Missions and Sample Return and Other Missions (NASA, 2002b). Scout Missions are planned to begin in 2007, and are designed to explore the Martian atmosphere and environment. Sample Return and Other Missions are scheduled to begin in 2014, but perhaps as early as 2011. The JPL states that the technological development for miniaturized surface science instruments will be carried out during this time period (NASA, 2002b), which ties into the anticipated timeframe for GEMS development. It will also be feasible to use GEMS for the exploration of other objects in the solar system including the Earth. Jupiter and its satellites are especially enticing targets for future exploration by distributed probes and can be considered when developing long-term system concepts.

SUMMARY

This paper highlights a novel observing system known as Global Environmental MEMS Sensors (GEMS) that will be designed and developed using advancements in microsystems and nanotechnology. The GEMS concept features an integrated system of probes that can provide in situ measurements with unprecedented spatial and temporal resolution for a variety of space missions. There are a number of key issues and enabling technologies summarized here that will be studied in detail to examine the potential performance and cost benefits, and develop a technology roadmap to integrate the concept into future space missions. The application for planetary exploration focused on deployment and dispersion of probes for various scenarios on Mars that could provide atmospheric and ground sensing capabilities far greater than previous missions. Data collected by the probes would improve the ability to calibrate remote sensing data and extend the areas measured by localized landers. GEMS could also be used to monitor space weather and explore other objects in the solar system. The unique features of GEMS including probe size, cost, and the ability to provide measurements over a broad range of space and time scales could revolutionize planetary and space exploration in the near and far term.

ACKNOWLEDGMENTS

This work was supported by the NASA Institute for Advanced Concepts through a grant from the Universities Space Research Association and by ENSCO, Inc. with a subcontract to Charles Stark Draper Laboratory. The authors thank Draper personnel S. C. Paschall and D. K. Geller for help with simulations of probe deployment/dispersion and L. R. Fuhrman for comments on an earlier draft of the paper.

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