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### **Microinstruments and Micro Electromechanical Systems In Support of Earth And Space Science In The New Millennium**

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# MICROINSTRUMENTS AND MICRO ELECTROMECHANICAL SYSTEMS IN SUPPORT OF EARTH AND SPACE SCIENCE IN THE NEW MILLENNIUM

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## Abstract

NASA's New Millennium Program (NMP) has been chartered with flight validation of next generation technology to demonstrate the feasibility of pursuing unmanned space science with low cost, miniature spacecraft and probes. In defining a roadmap for instrument development, primary emphasis has been placed on system concepts which take best advantage of instrument miniaturization. In this paper the "sensorcraft", which consists of an instrument in a minimal spacecraft architecture, is featured. Focus is on the specific example of the proposed Mars Microprobe, a vehicle of less than 5 kg mass which is deployed in a single stage from space to a planetary surface.

It is paradigmatic in spacecraft systems, and particularly in space instruments, that improvements in specific components, which do not themselves consume extensive resources, can have a revolutionary effect on the size and performance of the entire system. In the area of remote sensing, for example, requirements on light gathering ability have been substantially reduced by highly efficient focal planes (such as CCDs and Active Pixel Sensors) as well as image enhancement algorithms. This has enabled the reduction in size of optical systems from Voyager scale to integrated camera spectrometers weighing less than 5 kg, such as those developed for the proposed Pluto Express mission. Spectroscopy has similarly been advanced by the ability to microfabricate optical elements and to disperse light across focal planes with very small pixel size.

New imaging techniques involving synchronized spacecraft (interferometry, stereo imaging) dramatically increase the information content of images, and the promise of deployable optics will enable telescope designers to develop high resolution optics in small packages. Radiometry has been revolutionized by MMIC technology and multichip integration, while higher frequency measurements have reduced the mass and volume budgets associated with antenna structures and feedhorns. New materials such as silicon carbide and totally athermal systems also minimize the structural mass of optical benches.

While optical systems are typically components of complex, multifunctional spacecraft, a somewhat different situation applies to *in situ* science instruments (direct measurements of physical and chemical phenomena as well as particles and fields in the

vicinity of the probe). In this area, the approach is to de-emphasize "bolt-on" instruments in favor of probes designed around the instrument, or "sensorcraft". The sensorcraft can then be deployed in a number of different ways. Of greatest immediacy is the scenario in which a conventional spacecraft carries several miniature probes to the vicinity of the science target, where they can be deployed under their own power to their destination. The parent craft can then gather data from the probes and serve as a relay station back to earth. Examples of such sensorcraft include "free-flying" particle and field sensors (e.g. a boom-less magnetometer) as well as miniature landers and penetrators for exploration of planetary bodies. Other options for deploying sub-kg instruments range from microfabricated ion propulsion systems to solar sails.

The recent popularity of silicon-based micro electromechanical systems (MEMS) has spurred the development of a class of sensors which are so small that instrument systems built around them will always be dominated by electronics, sample acquisition, thermal control, apertures, and other system considerations. The challenge for the space science community is to integrate these new miniature sensors, built using MEMS and other "MEMS-like" technologies, into measurement systems compatible with space exploration.

MEMS are mechanical devices manufactured in much the same way as integrated circuits. A computer-generated lithographic pattern is transferred to a planar substrate consisting of layers of semiconductor, metal, and insulating material. Subsequent processing produces three dimensional structures which perform complex electronic functions. Unlike conventional

integrated **circuits**, MEMS devices use the electronic circuits to sense or actuate the *motion* of certain features of the pattern which are free to move as a result of **selective** chemical etching of surrounding material. In this respect, MEMS are equivalent to tiny *in situ* instruments. A common example of a MEMS device is the **accelerometer** used for deploying automotive **airbags**. While MEMS devices have potential uses in communications, thermal **management**, inertial guidance, and propulsion, the most immediate application is for *in situ* sensors.

### Evolution of an instrument

Three specific goals of instrument development are enabling for space systems.<sup>2</sup> The first, and most obvious, is miniaturization. Miniaturization allows **experiments** to be carried **into** space which were previously only feasible in earthbound **laboratories**, allows small experiments to be co-manifested with other spacecraft, or allows network science. For example, through the use of radioactive sources to replace particle and photon beams, techniques such as **Rutherford backscattering** or photoelectron spectroscopy can be **miniaturized** for space. Similarly, through the use of diode lasers, techniques such as Raman spectroscopy can be **miniaturized** for space. implicit in miniaturization is reduction in required **system** resources such as power, cooling, and structural support.

The second identified goal is new functionality. Aggressive space exploration calls for **measurement** tools and techniques unnecessary or inappropriate on **Earth**. New types of measurements specifically applicable to space are being developed, such as neutral atom imaging mass spectrometers and a variety of geochemistry tools for cold, dry soil. An entirely new area of concern is the development of instruments specifically to validate the performance and byproducts of other new spacecraft technologies, such as plasma **analyzers** to characterize solar electric propulsion systems.

The third goal of "instrument autonomy" is both more subtle and more profound in its implications, as it arises from a system view of an instrument and its relationship to a spacecraft. In addition to a sensor, an instrument consists of a mechanical structure, **deployment** mechanisms, sample handling **devices**, power management and/or sources, analog and/or digital electronics, data processing and communication

resources. All of these instrument subsystems interact with the spacecraft in some manner. For example, a **conventional instrument** transmits data over a serial line to a spacecraft computer. In the instrument of the future, this is likely to be a wireless link. Traditional **instruments** receive power from the spacecraft. Future low power instruments are likely to carry their own batteries. Embedded processors are becoming commonplace, replacing a **dependence** on central spacecraft processors.

Key to instrument autonomy is mobility, which results in new approaches to sample acquisition technology, by bringing **the instrument** to the sample instead of vice versa. This category includes mobility in space (free flyers), in planetary atmospheres (balloons), on surfaces (rovers) and underground (**penetrators**).

In abandoning the protective shell of the spacecraft, the instrument is exposed to more **extreme** environments than in conventional practice. **Unprotected** by the radiation shielding of the spacecraft, for example, instrument electronics designers will need to be **attentive** to **radiation** hard fabrication and operation protocols. Mechanical shock often is extreme, particularly in landed packages. Of most general **concern**, however, is the thermal stress imposed on autonomous **instruments**, both static (**extremely** low and high temperatures) and dynamic (frequent temperature cycles).

The dynamic **problem** is one encountered on earth, for example, in under-the-hood automotive applications where 100K **temperature** swings are common. The **requirement** of operation at low temperatures is also reasonably well understood from terrestrial experience, and is compatible with common semiconductor **devices** (silicon and gallium arsenide, for example). The most severe constraint with respect to low temperature operation is battery technology, where little or no technology exists for operation below 200K. The high temperature operating environment (e.g. for Venus landers) is poorly developed with respect to electronics, and would require breakthroughs in, for example, silicon carbide based semiconductor circuitry.

In short, the instrument of the future "asks less" of the spacecraft. It is more autonomous, and may only require a parent spacecraft to bring it to the vicinity of its **measurement** locale and to relay data back to Earth. The following table attempts to capture this evolutionary direction:

**TABLE I: EVOLUTION OF AN INSTRUMENT**

Subsystem	Conventional Instruments	Future instruments
<b>Power</b>	Provided by spacecraft	Batteries & photovoltaics
<b>Data &amp; Telecom</b>	Serial link to spacecraft	Wireless link
<b>Sample handling</b>	Sample received from spacecraft	Instrument is mobile, travels to sample
<b>Structure</b>	Bolted onto spacecraft	Free flying, mobile
<b>Electronics</b>	Analog and ADC	Analog circuits and embedded processors, data reduction, local networks
<b>Deployment</b>	Shutters, booms, platforms, arms	Full mobility, including micro propulsion

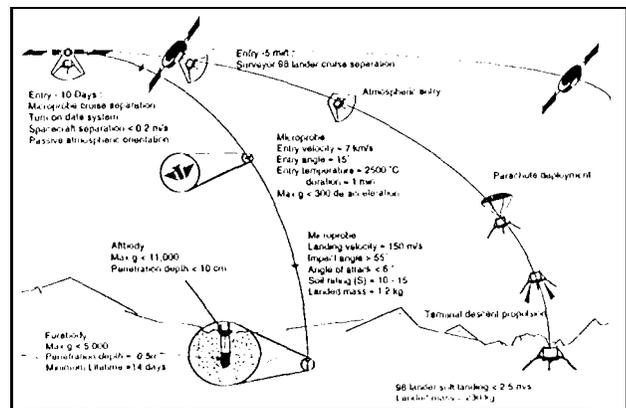
The balance of this paper will focus on the *in situ* sensorcraft as epitomized by the Mars Microprobe.

**The Mars Microprobe**

A specific example of an autonomous instrument for *in situ science* is the Mars Microprobe which is being proposed for NMP validation in 1998.3 This probe typifies the above concepts in that meaningful science is to be performed by instruments weighing substantially less than 1 kg (miniaturization), the entire package is to be deployed from space in a vehicle weighing less than 5 kg (autonomy) and the measurements themselves have not previously been applied to planetary surface science (new functionality). The Microprobe represents nearly two orders of magnitude reduction in mass compared to conventional landers (e.g. Mars Pathfinder and Mars Surveyor). While the quantity of scientific data that can be returned by a single such microprobe will be less than that of a conventional lander, networks of

microprobes can be deployed around the planet using no more resources than a single landing under conventional assumptions.

A schematic of the microprobe deployment from the Mars Surveyor Lander (MSL) cruise vehicle is shown in figure 1. The microprobe is separated from the cruise stage several days prior to deployment of MSJ.. A small penetrator consisting of a fore and aftbody linked by an umbilical is nestled inside an aeroshell. The microprobe remains intact with no deployment of braking devices until impact, when the penetrator pierces the aeroshell and buries itself in the soil. The aftbody remains on the surface to perform meteorological and communication functions.



**Figure 1: Proposed deployment of the Mars Microprobe as part of NASA's 1998 Mars Surveyor Lander Mission showing release from cruise vehicle, aeroshell breaking, and fore-and-aftbody deployment on the ground**

The unusual deployment of the microprobe poses a particular instrument integration challenge. Obviously, instruments must be designed to withstand mechanical shocks associated with impact. Since microprobes lack resources to effectively control the thermal environment, the instruments must also be designed to operate at low temperatures and to survive the stress of frequent thermal variation. To save weight, the system must operate on minimal power. In the initial implementation power will be limited to the few watt-hours provided by lithium batteries, so all subsystems must operate in burst-and-sleep mode with low duty cycle. Subsequent generations will no doubt deploy photovoltaic cells for continuous power.

Deployment of the forebody 50-100 cm beneath the surface is a unique feature of the microprobe as

compared to conventional landers. The layer of soil above the **forebody** serves to cushion the impact, insulate the probe from severe diurnal and seasonal **temperature** variations, and protect **instruments** from wind, radiation, and other sources of noise. Only **select** components such as antennas and meteorological sensors are required to be placed in the substantially more hostile aftbody on the surface.

### Survivability

What enables the accomplishment of **instrument** deployment from such a small vehicle is the strategy of single stage **aerobraking** using a low ballistic coefficient **aeroshell**. The impact velocity can be **determined** with reasonable accuracy from the mass  $m$  and frontal area  $A$  of the **aeroshell**,

$$v_i = (2mg/\rho_{air} A C_d)^{1/2} \quad (1)$$

where the density of **martian air**  $\rho_{air} = 0.01 \text{ kg/m}^3$ , the drag coefficient  $C_d = 1.7$ , and  $g = 3.74 \text{ m/s}^2$  on Mars. The microprobe package is designed for impact velocities of 50-200 **m/s**, which translates to a frontal area of **approximately**  $0.1 \text{ m}^2$  for 1-3 kg probes. It is only for probes of such small size that survivability can be achieved with acceptably compact **aeroshells**, and it is only by eliminating more **complex** braking mechanisms (parachutes, rockets, or airbags) that such small sizes can be achieved.

Survivability of instrumentation under high impact deployment is dependent both on the deceleration profile and the instrument packaging. In simplest terms, the average  $g$  loading is related to the impact velocity  $v_i$  and the penetration depth  $d$  by the equation  $a = v_i^2/2d$ . The intended penetration depth of 50-100 cm indicates that loads of 1000-10,000  $g$  must be tolerated in the proposed implementation ( $g = 9.8 \text{ m/s}^2$ ). Note that the depth of penetration is approximately proportional to the **impact** velocity, with the result that the average deceleration of the **forebody** increases linearly with the impact velocity rather than quadratically,

In general, it is commonplace for **small rigid devices** (such as electronics) to survive impacts of tens of thousands of  $g$ 's in applications ranging from ballistics to **sporting** equipment. It is important to **remember** in this context that impact-related damage is more dependent on the **force** applied than on the specific acceleration. Thus a 1 kg object suffering a 10,000  $g$  impact might be expected to pose a similar packaging

**challenge** as a 330 kg object at 30  $g$  (the approximate conditions of the Mars Pathfinder landing). While the detailed damage analysis is dependent on the propagation of the shock wave through the structure, it should be noted that the greatest damage is **suffered** when the resonant frequency of a particular structure is strongly excited. This is **less likely** to happen to small, rigid bodies with high resonant frequencies than to larger, more conventional instruments.

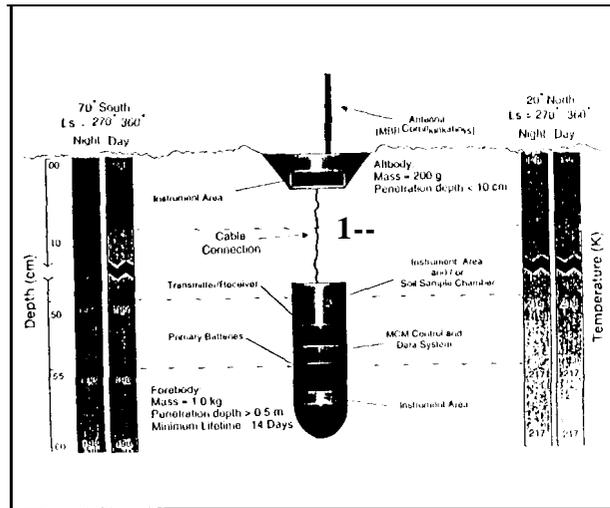
Since the microprobe lacks active attitude control, it **must** be self-righting when it enters the atmosphere from space. It must maintain a small angle of attack (**less than**  $6^\circ$ ) in the presence of possible winds and turbulence in order to ensure proper operation of the **penetrator**. In addition, the **instrument** package must survive the thermal pulse associated with **aerobraking**. This pulse is comparable to that **experienced** by larger low ballistic coefficient entry vehicles. From first principles it can be expected that the dependence of the **aeroshell** temperature is only weakly dependent on the **aeroshell** size if the ballistic coefficient is maintained constant. If  $r$  is the **aeroshell radius**, the heating rate  $q$  is approximately proportional to  $r^{0.5}$ . If most of the mass  $m$  is in the shell itself,  $r$  is in turn proportional to  $m^{0.5}$ . If the maximum **aeroshell temperature**  $T$  is determined by radiative balance, then  $q$  is proportional to  $T^4$ , and it follows that  $T$  varies as the  $1/16$  power of the mass of the entry vehicle. Detailed calculations bear out this assumption, and predict a maximum **temperature**  $T_{max} \sim 2 \text{ 100K}$ . The various carbon composites being considered for the **aeroshell** can survive heating to these temperatures without mechanical failure. Since the heat pulse will last **only** for tens of seconds, the small payload can easily be thermally shielded without the addition of substantial mass.

### System Resources

A schematic of the **penetrator** configuration is shown in figure 2 (the actual geometry will have a far more complex three dimension structure than shown). Typical resources for **first** and second generation microprobes are shown in Table 2:

**Microprobes** can be used to investigate both soil and atmosphere, and potentially can perform **measurements** during **descent**. For meteorology or atmospheric chemistry, probes must be deployed from the **aftbody** (although the primary measurement of atmospheric pressure can possibly be made from the subterranean **forebody**). **Measurements** of homogeneous quantities

such as relative humidity or isotopic ratios can be made directly from the **forebody**, while measurements of temperature and wind are best made at a distance on the order of a meter from the ground. The latter requires either the development of light weight deployable masts, or the use of remote measurements such as short range I.DAR.



**Figure 2. Schematic of resource allocation on Mar Microprobe, indicating power, communication, electronics, sample acquisition, structure, and instruments.**

The most straightforward **forebody** measurements to make are those which do not require acquisition of a discrete sample. Such measurements include **seismometry** as well as physical and chemical probes (heat conductivity measurements with arrays of thermocouples or radiometric methods including nuclear magnetic resonance). Measurements of soil characteristics which require active manipulation of samples are more **problematical** in that undisturbed specimens must first be acquired. In the first generation implementation, sampling will be done passively by allowing soil to fall into a receptacle as the **penetrator** comes to rest. This approach has the liability that the sample comes from a single depth, and may have been perturbed by the passage of the **penetrator**. In general, heating effects are most worrisome, and are currently under study. They are expected to average about 10°, but the distribution may be uneven. The optimal method to characterize soil in future implementations will be via miniature, self-propelled digging tools which can retrieve undisturbed samples from different depths.

### Microprobe instrumentation

While successful deployment of a microprobe demonstrates the feasibility of low-cost network science on Mars, the actual scientific value is dependent on the capability of instruments which can be developed to operate within severely constrained resources. A number of sensors have been proposed for early demonstration, some of which are described below. The proposed 1998 Microprobe demonstration will select only a limited subset of these instruments.

### Impact accelerometry

Most terrestrial instrumented penetrators rely on inertial measurements as a primary source of geological information. The most usual approach is to measure three orthogonal axes with piezoresistive accelerometers which detect beam deformation with strain gages. Other modes of motion (e.g. torsional) are typically of less relevance, as the primary information of interest is the hardness of the layers being passed through. Of particular importance in the Mars polar regions is the passage from a dust or soil layer into an ice layer, which should be readily detectable by this method. In addition, information about the success of the deployment (e.g. the deployment depth and rest orientation of the penetrator) can be determined. Commercially available accelerometers with adequate performance occupy volumes substantially less than 1cm<sup>3</sup> per axis.

### Meteorology

The two primary objectives of Mars network science are meteorology<sup>4</sup> and seismometry<sup>5</sup>. Of the meteorology measurements, pressure is the most tractable in that deployment of the sensor is not critical to the measurement. The temperature of the pressure sensor itself must be monitored, but measurement of air temperature itself is a challenging task requiring establishment of an equilibrium between the thin atmosphere and the sensor. Like pressure, measurement of relative humidity is not highly sensitive to sensor deployment, while wind speed measurement is highly deployment critical.

Pressure measurement in the 10 mbar range can be accomplished in a number of ways. Several commercial silicon micromachined pressure sensors operate in this range and at least one, fabricated by Vaisala, Inc. of Finland<sup>6</sup>, is sufficiently accurate and compatible with this mission. These sensors are effectively miniature capacitance manometers utilizing sealed reference cavities separated by a thin silicon nitride membrane from the ambient.

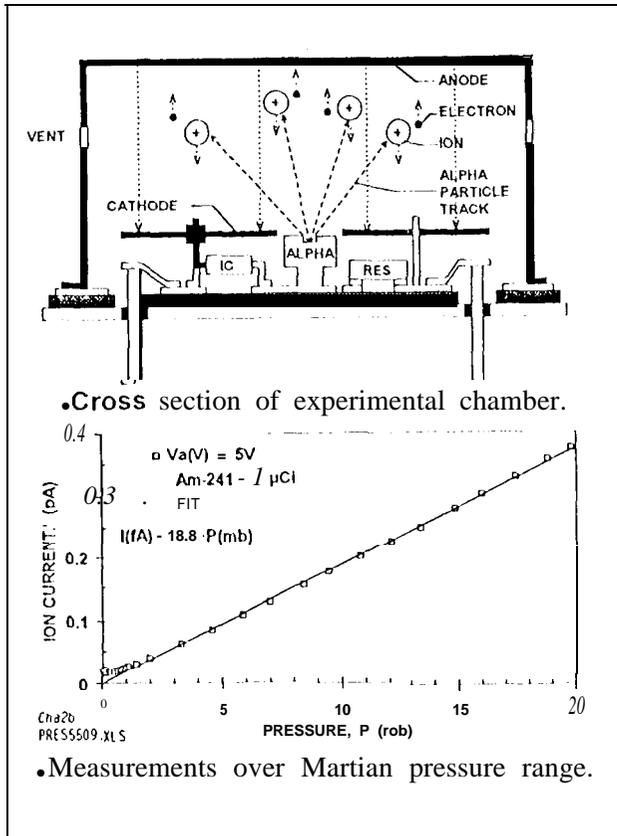


Figure 3: Top - Schematic of the alpha particle pressure sensor. Bottom - Calibration data over the range of interest for martian meteorology (the nonlinearity near zero is electronic in nature and has subsequently been eliminated).

An approach which, while less mature, is more suited to this low pressure range, is to use the ionization method commonly applied in high vacuum in the form of a Bayard-Alpert gauge. In this method, a constant flux of ionizing particles traverses the sample region and a small fraction collide with the residual gas to produce positive ions which are collected and amplified. Although commonly referred to as a pressure measurement, the technique actually measures

atomic density, which is related to pressure and

TABLE II: Microprobe Resources

	First Generation	Second Generation
Power	1-5 Watt-hr	1 W continuous
Data Volume	<1 MB	500 MB
Lifetime	500 hrs.	20,000 hrs.
Instrument Volume	<50 cm <sup>3</sup> (forebody)	<50 cm <sup>3</sup> (forebody)

temperature through the ideal gas law. Unlike the manometer, the response to the ionization sensor is species dependent (not a problem for the Mars atmosphere which consists primarily of CO<sub>2</sub>). In high vacuum, the ionizer typically consists of a hot filament or cold cathode. For atmospheric pressure, the technique can be implemented by replacing the cathode with a small alpha emitter such as the Am<sup>241</sup> source commonly used in commercial smoke detectors. Such a sensor has been developed and tested, and can be fabricated to fit within the mass and volume allocation of the aftbody (figure 3).

A quantitative measure of atmospheric humidity is determination of the dewpoint or frostpoint by detection of condensation on a surface. In commercial systems, this is accomplished by monitoring changes in optical reflectivity on a chilled mirror surface. The range, response time, and energy consumption of these devices is limited by the ability to heat and cool the mirror. A smaller, faster, lower power implementation of a dewpoint hygrometer has been developed at JPL by coupling a surface acoustic wave oscillator (SAW) to a small thermoelectric cooler.\* As moisture accumulates on the SAW a small shift in the resonant frequency is observed. A feedback circuit maintains the SAW temperature at the dewpoint so that nonlinearities of the frequency response or the sticking probability do not degrade the measurement.

The SAW dewpoint hygrometer occupies less than 1 cm<sup>3</sup> and, since the surface to be cooled is so small, can be operated down to 40 degrees below ambient temperature using less than a watt. As can be seen in figure 4, the response time of the miniature dewpoint hygrometer is substantially faster than the chilled mirror counterpart, representing a case where superior

performance is actually achieved with the microprobe-compatible instrument.

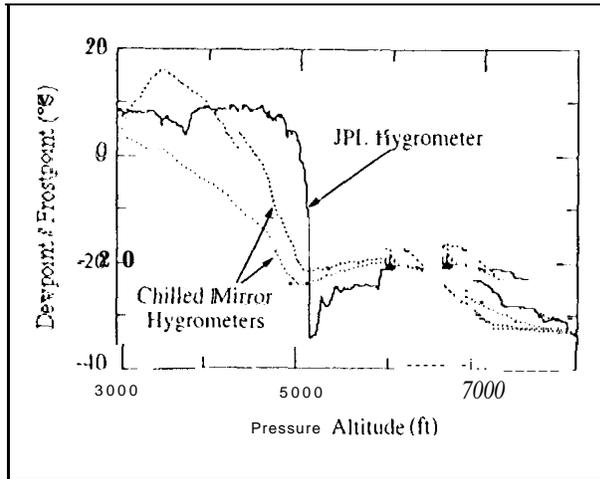


Figure 4: Data from a DC-8 test flight comparing the response time of a SAW dewpoint hygrometer to conventional chilled mirror devices.

#### Seismometry

Seismometry is a key objective of Mars network science, yet no capable seismometers exist outside the laboratory which can meet the resource requirements of the Microprobe. The challenge is the greater due to the fact that Mars is seismically quieter than the quietest location on earth, and requires more sensitive instruments than those deployed on earth. All seismometry signals associated with the Viking mission could be attributed to wind, and it was only possible to conclude that Mars is not seismically more active than Earth.

It is desirable for Mars seismometers to have sensitivities approaching  $10^{-12} \text{ g}/\sqrt{\text{Hz}}$ . This sensitivity requires a delicate proof mass that must be caged to survive impact. Seismometers are required to measure long period phenomena up to tens of thousands of seconds, so extremely low drift is a requirement. The principle source of drift in seismometers is thermal, and the martian surface, with a diurnal temperature variation of tens of degrees, poses a serious impediment to seismometry. As indicated in figure 2, however, at depths of greater than 50 cm the diurnal variation is less than one degree, and the stability problem becomes simpler. This is a compelling argument for subsurface deployment. Of greatest importance, however, is the fact that subsurface

deployment reduces the wind effects which plagued the Viking seismometer by several decades.

A seismometer developed at JPL for microprobe deployment<sup>9</sup> utilizes a micromachined, 1 mm thick silicon proof mass weighing approximately 1 gram (figure 5). The proof mass is highly symmetrical and has a resonant frequency of approximately 10 Hz. While this is a relatively high frequency as compared to conventional seismometers, the increased rigidity substantially improves the shock resistance and reduces long-term drift. A more rigid proof mass suffers smaller displacement in response to a seismic impulse, implying that the displacement pickoff must be substantially more sensitive than the transducers in more conventional instruments with softer springs. This is accomplished by means of an innovative high frequency capacitive measurement slightly detuned from resonance. The result is a measured response of better than  $10^{-9} \text{ g}/\sqrt{\text{Hz}}$ .

Substantial compensation for the decreased range of motion is the fact that the highly flat proof mass is compatible with very small gap capacitors, resulting in a larger relative change in capacitance signal for comparable motion ( $\Delta C/C \propto \Delta x/X$ ) where  $\Delta C$  is the change in capacitance resulting from a change in gap  $\Delta X$  due to a seismic motion. In the microprobe implementation, the capacitor gap is 0.01 mm, resulting in a nominal capacitance range of 10-25 pF. The seismometer operates in a force feedback mode to improve linearity and dynamic range.

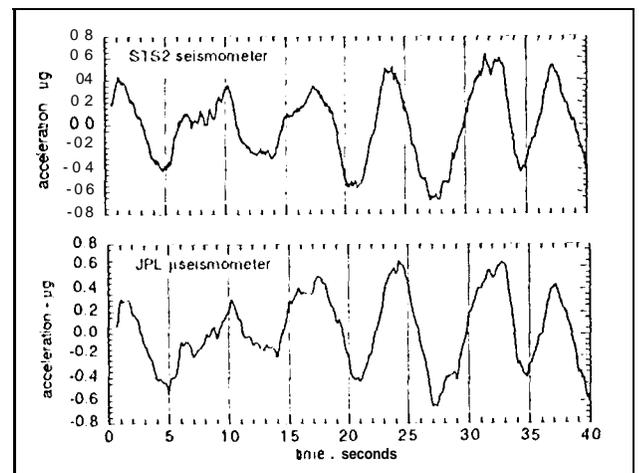


Figure 5: Data from a miniature seismometer with a micromachined proof mass as compared to a conventional unit.

### Chemical sensors

Chemical sensors for terrestrial applications are of two distinct varieties. The most common measure the modification of thin films or activated surfaces due to the adsorption of a chemical species. This approach lends itself to extremely inexpensive, compact, low power sensors. However, while the films and surfaces are designed to be specific to the target species, this mechanism is intrinsically prone to cross-sensitivity and poisoning. Such sensors are of greatest benefit when the environment is well characterized, such as monitoring for leaks in specific toxic gas handling systems. They are of least value in poorly characterized environments unless arrays of different sensors are examined for signature responses.

An example of such an array is the Mars Oxidation Experiment (MOx) which is to be flown on the Russian Mars '96 mission<sup>10</sup>. MOx uses a photodiode array, light emitting diodes, fiber bundles, and a microfabricated optical bench to monitor changes in reflectivity of a large number of thin tires in contact with martian soil and atmosphere. An advantage of this type of measurement is that it is completely passive. The reaction continues even when no power is applied to the system.

The second variety of sensor uses spectroscopic methods to uniquely identify chemical species. Such sensors are intrinsically more complex and expensive, but are also more definitive and quantitative. In most cases, spectroscopic sensors are also broad spectrum, and can completely characterize a complex mix of materials. It follows that an important goal for *in situ* sensor development is to miniaturize spectroscopic sensors for deployment in unknown environments. A key instrument is the mass spectrometer, which is available commercially<sup>11</sup> in acceptably small format. Daunting system issues, particularly pumping and power usage, remain to be resolved before deployment of this type of instrument is possible on microprobes.

### Evolved Water Experiment

The leading candidate for verification of successful acquisition of a soil sample is the Evolved Water Experiment (EWE). This experiment uses a Tunable Diode Laser (TDL) spectrometer<sup>2</sup> to quantitatively measure the water content of gases which are thermally desorbed from a soil sample. The objective of the experiment is to determine the dominant mineral phase and abundance of water in the soil, and to determine presence or absence of ice near the surface. Wet soils

(>10 wt. % water) such as smectite clays or palagonites are suggested by certain Viking data (X-ray fluorescence, labelled release) and remote sensing data, while dry soils were implied by the Viking Lander gas chromatography mass spectrometer experiments.

The TDL spectrometer is a miniaturization of a class of spectrometers which have previously been deployed from airplanes for atmospheric chemistry. The complete system consists of a temperature-controlled laser, detector, optics, electronics, and gas manifold. The TDL itself typically has a linewidth of  $.0003 \text{ cm}^{-1}$ , which is more than adequate for resolving distinct spectral lines due to overtone excitations of many common species. To produce a spectrum, the TDL can be scanned across several wavenumbers by ramping the input current. The central wavelength can be selected by controlling the laser temperature with a thermoelectric cooler. Such a spectrometer is capable of detecting  $\text{CO}_x$ ,  $\text{NO}_x$ , and other isotopes, with better than parts per billion sensitivity.

Since sensitivity depends on pathlength, the typical TDL spectrometer uses a Herriott cell to fold the optical path many times in a limited volume. In addition, since the input current ramp results in a sloping background, the data is typically acquired in second harmonic mode to remove both slope and offset. The state-of-the-art system is shoe-box sized, and is coupled to an external computer. By contrast, the EWE spectrometer is required to detect water above the martian background partial pressure of  $1 \text{ mTorr}$ , or 1 part in  $10^5$ . With a 1370 nm laser, the minimum detectable water is expected to be 15 ppmv within a pathlength of 2.3 cm. Electronics will be implemented using ASIC and MCM technology to reduce size and power consumption and increase survivability.

The objective of the EWE is to determine the evolution of water from a soil sample subject to controlled heating of several hundred degrees centigrade. The 0.1- 1.0 g soil sample is sealed in a collection cup by a simple mechanism, and is heated by a battery-powered coil at a rate of approximately  $30^\circ$  per minute. The evolved gas passes through a porous plug into a portion of the analysis chamber isolated from the laser and detector by a quartz window which is tilted to avoid specular reflection. The walls of the chamber are heated only enough to avoid condensation within the defined instrument measurement range. Gases are continuously vented with a flow impedance optimized for the measurement rate. Since there is a continuous flow from the sample through the measurement volume, an important objective of the test and

modelling program is to quantitatively associate soil water content with the measured gas concentration.

The total mass of the EWE is under 200 g in a volume of < 40 cc. The power consumption is estimated at 2 W for 20 minutes, primarily for sample heating.

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12. See, for example, C.R. Webster, R.D. May, C.A. Trimble, R.G. Chave, J. Kendall, "Aircraft (ER-2) laser infrared absorption spectrometer (ALIAS) for *in-situ* stratospheric measurements of HCl, N<sub>2</sub>O, CH<sub>4</sub>, NO<sub>2</sub>, and HNO<sub>3</sub>", *Appl. Opt.* Vol. 33, p. 454, 1994.