# MEMS TECHNOLOGY FOR SPACE APPLICATIONS

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## Introduction

NASA's New Millennium Program (NMP) has been chartered with flight validation of "leapfrog" technologies in support of unmanned space science using low cost, miniature spacecraft and probes. NMP has utilized a two-pronged approach of using innovative mission concepts (e.g. separated spacecraft interferometers) as testbeds for new technology at the component level. The latter is the charter of six Integrated Product Development Teams (IPDTs) representing a mix of government, industry, and university partners.

While micro electromechanical systems (MEMS) is a cross-cutting technology, primary responsibility for developing the MEMS roadmap resides with the IPDT for In Situ Instruments and MEMS (ISIM), which consists of members from JPL, Southwest Research Institute, Sandia National Laboratory, Stanford University, Los Alamos National Laboratory, and Air Force Phillips Laboratory. *In situ science* instruments are those that provide direct measurements of physical and chemical phenomena as well as particles and fields in the vicinity of the probe. While MEMS devices have potential uses in communications, thermal management, inertial guidance, and propulsion, the most immediate application for NASA is for *in situ* sensors. Although this is the primary motivation for the pairing of the two technologies, it is also noteworthy that MEMS are, in themselves, tiny *in situ* instruments

The ISIM IPDT has emphasized definition of system architectures which benefit from and justify the development of sensors, instruments, and MEMS components which are decades smaller than those in conventional use.[1] It has also addressed issues of validation and qualification of MEMS devices for space.[2] This paper will lay out the principles which govern the prioritization of technologies, and will give several detailed examples. ISIM does not make a distinction between true MEMS and other miniature "MEMS-like" technology, and for the sake of simplicity these technologies will be referred to generically as MEMS.

## General principles

Principle 1: MEMS can not be justified for use on **conventional spacecraft** on the basis of per-unit fabrication cost, **size**, or **power** alone, nor typically for performance, reliability, or **robustness**. MEMS typically do not perform better than their conventional counterparts and, because of their novelty, typically introduce greater risk into critical space missions. Reduced unit cost, which justifies much of commercial MEMS development, seldom impacts the life cycle cost of a science-oriented spacecraft. In a spacecraft weighing hundreds of kilograms, replacement of a one kilogram science sensor by a MEMS device. weighing a few grams does not have enough impact to justify the increased risk.

The above is not intended to imply that opportunities for MEMS are not plentiful. For many spacecraft applications there are tremendous mass multipliers, either because large numbers of sensors must be deployed or, for example, because kilograms of cryogen are required for each gram of sensor. In certain instances MEMS devices offer critical performance advantages, such as in high impact applications. By far, however, the greatest opportunity for MEMS *is* in the context of a completely re-engineered probe in which all subsystems are miniaturized to MEMS scale. As will be discussed below,, this can be achieved in the near term for carefully selected applications where full spacecraft capability (particularly propulsion, navigation, and deep space communication) are not required.

Principle 2: It is easy to recognize things that work well on a large scale but poorly on a MEMS scale. It is **harder** to **recognize** things that work poorly on a large **scale** but well on a **MEMS** scale. A good example of this phenomenon is propulsion and braking technology. Valves leak badly on the MEMS scale, and are a limiting factor in implementing micropropulsion systems. Direct sublimation of solid fuel, which can be slow and poorly controlled on a large scale, can be extremely precise on a MEMS scale due to the low thermal mass and short time constants. Photon pressure propulsion systems, which would require square kilometers of solar sails for conventional spacecraft become feasible and attractive for small enough payloads. High impact landing works well on a MEMS scale, as does aerobraking (see below), but parachutes don't work well because of the sensitivity to winds.

Principle 3: **Development** of advanced ***in situ*** instruments must support an evolutionary trend towards **instrument autonomy.** Key to instrument autonomy is severing of the umbilical which ties the instrument to the spacecraft. Typical science instruments consist of one or more sensors, a mechanical structure, deployment mechanisms, sample handling devices, power management and/or sources, analog and/or digital electronics, data processing and communication resources. For example, a conventional instrument transmits data over a serial line to a spacecraft computer. Using current technology, this line can be replaced by a wireless link. Traditional instruments receive power from the spacecraft. Many low power instruments can now be run entirely from small, long-life 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 of probes or "sensorcraft" 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 earbide 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 tc, 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 1: EVOLUTION OF AN INSTRUMENT

| **Subsystem** | **Conventional** Instrument | **Future Instruments** |
|---|---|---|
| Power | Provided by spacecraft | Batteries & photovoltaics |
| **Data & Telecom** | Serial link to Spacecraft | Wireless link |
| sample handling | Sample received from spacecraft | Instrument, travels to or through sample |
| **Structure** | Bolted on to spacecraft | Self-contained, integrated with function |
| **Electronics** | Analog and ADC/DAC functions | Analog circuits and embedded processors, dara reduction, local networks |
| **Deployment** | Shutters, berm platforms, arms | Full mobility, including micro propulsion |

## The Mat-s 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, and the entire package is to be deployed *from space* in a vehicle weighing less than 2 kg The Microprobe is a small penetrator consisting of a fore and aftbody linked by a cable, and nestled inside a one-piece aeroshell approximately 30 cm in diameter. Note that 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 (parachute, rockets, or airbags) that such small sizes can be achieved. The microprobe remains intact with no deployment of braking devices until impact, when the penetrator pierces the aeroshell and buries itself in the soil. There it can perform geological and mineralogical measurements. The aftbody remains on the surface to perform meteorological and communication functions. While the quantity of scientific data that can be returned by a single such microprobe "will be leas than that of a conventional lander, networks of microprobe can be deployed around the planet using no more resources than a single landing under conventional assumptions.

The unusual deployment of the microprobe poses a particular instrument integration challenge. Electronics, telecommunications, and power subsystems utilize rugged multichip module construction. Instruments must designed to withstand mechanical shocks associated with impact. In addition, since microprobe lack resources to effectively control the thermal environment, the instruments must also be designed to operate at Iow temperatures and to survive [he stress of frequent thermal variation. To save weight, the system must operate on minimal power. [n 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 are expected to deploy photovoltaic c-ells 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 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 ($g=9.8\ m/s^2$) 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. It is the small size of the penetrator, of course, that provides survivability under these high impact conditions.

Typical resource-s for first and second generation microprobe are shown in Table 2:

TABLE 11: 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$^3$ (forebody) | <50 cm$^3$ (forebody) |

While successful deployment of a microprobe demonstrates the feasibility of Iow-cost network science on Mars, the actual scientific value is dcpcndcnt on the capability of instruments which can be developed to operate within severely eonstrained 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.

### *Meteorology*

'l'he two primary objectives of Mars network science are meteorology[4] and seismometry[5]. The atmospheric pressure is approximately 10 mbar, and can bc measured by micromachincd sensors[6]. These are typically capacitance manometers utilizing sealed reference cavities separated by a thin silicon nitride membrane from the ambient.

An approach more suited to this low pressure range is a variation of the 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. For atmospheric pressure, the technique can be implemented by replacing the hot filament ionizer with a small alpha emitter such as the $Am^{241}$ source. used in commercial smoke detectors. Such a sensor has been developed to fit within the mass and volume allocation of the aftbody (figure 1).[7]

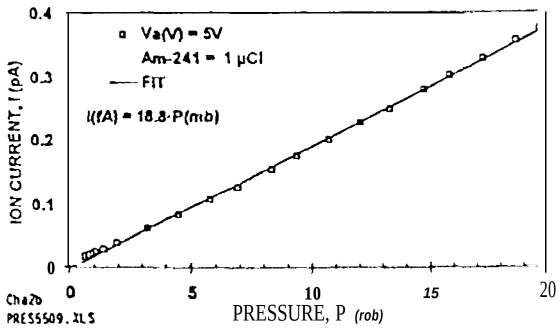

**Figure** 1: Top - Calibration data for alpha particle pressure **sensor** (the nonlinearity near zero is electronic in **nature** and has subsequently been **eliminated).**

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) with a small thermoelectric cooler.[8] 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.

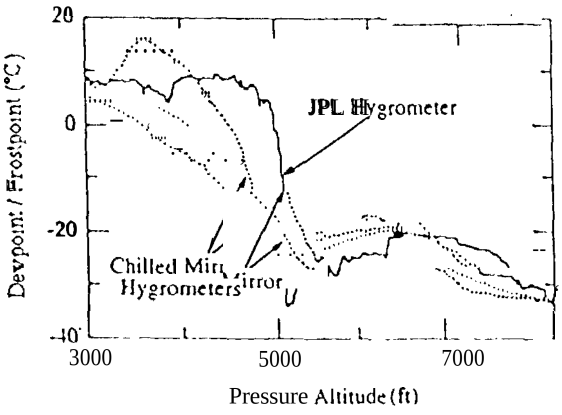

**Figure** 2: Data **from** a DC-8 test flight comparing the **response time** of **a** SAW **dewpoint hygrometer** to **conventional** chilled mirror devices. (Note that the aircraft is descending, and time increases from right to **left).**

The SAW depoint hygrometer occupies less than 1 $cm^3$ 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 2, the response time of the miniature dewpoint hygrometer is substantially faster than the chilled mirror counterpart.

*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 $10^{-12} g/\sqrt{Hz}$. 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 principal 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. At depths of greater than 50 cm, however, 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 by several decades.

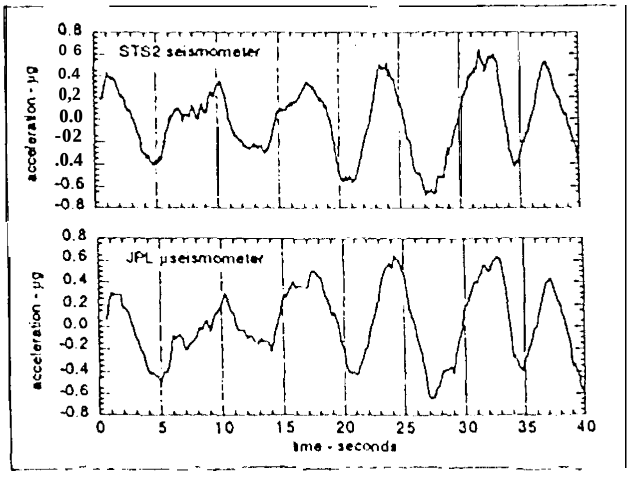

Figure 3: **Data from** a miniature seismometer with a **micromachined** proof mass as **compared** to a conventional unit.

A seismometer developed at JPL for microprobe deployment utilizes a micromachined, 1 mm thick silicon proof mass weighing approximately 1 gram. 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, requiring the displacement pickoff to 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 $10^{-9}$ g/√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 (AC/C a AX/X) where ΔC is the change. in capacitance resulting from a change in gap AX 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.

### *Mineralogy*

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[12] 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.

The TDL spectrometer is a miniaturization of a class of spectrometers which have previously been deployed from balloon and aircraft platforms for atmospheric chemistry. The complete system consists of a temperature-controlled laser, detector, optics, electronics, and gas sample chamber. The TDL itself typically has a linewidth of .0003 $cm^{-1}$, which is more than adequate for resolving distinct spectral lines of many common species, even in low pressure Doppler-limited conditions such as those present on Mars. 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 any low molecular weight species having an absorption band within the accessible wavelength range of the laser, including isotopic variants (e.g. CO, $CO_2$, $NH_3$, $H_2O$) with better than parts per billion sensitivity.

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” 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.

## Acknowledgements

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## References

1. M. H. Hecht (1996), "Microinstruments and Micro Electromechanical Systems in Support of Earth and Space Science in the New Millennium”, *Proceedings of the AMA 34th Aerospace Sciences Meeting and Exhibit,* January 15-18, Reno, NV.

2. L. Muller, M. H. Hecht, L.M. Miller, H.K. Rockstad, J.C. Lyke (1996), “Packaging and Qualification of MEMS-Based Space Systems”, to appear in Proceedings of IEEE Workshop on MEMS, San Diego, CA, Feb. 11-15.

3. The Mars Microprobe is conditionally co-manifested on NASA’s 1998 Mars Surveyor Lander.

4. D. Crisp, W.J. Kaiser, T.R. VanZandt, M.E. Hoenk, J.E. Tillman (1995), “Micro Weather Stations for Mars”, *Acta Astronautica* V. 35, p. 407-415.

5. S. Solomon, D. Anderson, W. B. Banerdt, R. Butler, P, Davis, F. Dunnebier, Y. Nakamura, E. Okal, R. Phillips (1991), “Requirements for a Mars Global Seismic Network”, *L.P.I. Tech. Report* 91-02, Lunar and Planetary Institute, Houston

6. A.-M. Harri *et al (1993)*, "Qualification Test Report, METEGG sensor candidates in Martian Environments" Finnish Meteorological Institute Document METEGG-FMI-SEN-DOC-10/93, Issue 1.0, 2-June.

7. M. Buehler, L.D. Bell, M. H. Hecht ‘Alpha-Particle Gas-Pressure Sensor (1996) “, to appear in *J. Vac. Sci. Technol.* (presented at 42nd American Vacuum Society National Symposium, Minneapolis, Minn., October 18, 1995)..

8. M. E. Hoenk, T. VanZandt, WJ. Kaiser, D. Cheng (1995), “Direct Dewpoint Measurement with a Surface Acoustic Wave Hygrometer”, presented at 42nd American Vacuum Society National Symposium, Minneapolis, Minn., October 18.

9. G. Varsi, M. Chrisp, R. Jones, 1’. VanZandt, T. Kenny, W. Kaiser, W. Banerdt, E. Hui, D. Crisp (1992), “MicroInstruments and Microsensors for Space Science”, *Proceedings of World Space Congress*, Washington D. C., 28 August. COSPAR ID No. 1-M.3.04.

10. FJ. Grunthaner et. al. (1995), ‘Investigating the Surface Chemistry of Mars”, *Analytical Chemistry*, October 1, p. 605A.

11. RJ. Ferran & S. Boumsellek (1996), "High Pressure Effects in Miniature Arrays of Quadruple Analyzers for Residual Gas Analyis from $10^{-9}$ to $10^{-2}$ Torr", to appear in *J.* Vat. *Sci. Technol.* (presented at 42nd American Vacuum Society National Symposium, Minneapolis, Minn., October 18, 1995).

12. See, for example, C.R. Webster, R. I>. May, C.A. Trimble, R.G. Chave, J. Kendall (1994), “Aircraft (ER-2) laser infrared absorption spectrometer (ALIAS) for in-situ stratospheric measurements of HCl, $N_2O$, $CH_4$, $NO_2$, a’nd $HNO_3$", *Appl. Opt.* Vol. 33, p. 454.