

PACKAGING AND QUALIFICATION OF MEMS-BASED SPACE SYSTEMS

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ABSTRACT

The number of spacecraft designed and built over the next century will grow exponentially as communication satellite networks proliferate and NASA continues to push towards the development of many microspacecraft to replace its traditional "grand tour" space vehicles. Costs in the space industry are measured in terms of weight (dollars per pound launched) and reliability. Unit costs pale in comparison to launch costs and the cost of replacing an entire vehicle in the case of a catastrophic failure. Space systems present a unique application for microelectromechanical systems (MEMS) technology which can be applied to miniaturize many of the subsystems in a space vehicle, and can improve overall reliability.

This paper will identify potential applications of MEMS in a space system, describe space environmental factors, and review efforts to develop appropriate packaging and space qualification methodologies. Finally, a flight experiment for testing the performance of typical MEMS devices and packages in the space environment will be described.

INTRODUCTION

Many types of MEMS devices have been proposed for application to space systems in order to reduce size, weight, and power consumption at the component level [1,2]. At the same time, significant issues remain that have critical influence upon the viability of MEMS devices for space. As a new technology, the various classes of MEMS devices and the associated assembly and packaging approaches will require qualification for suitability of use in the space environment. Qualification specifications, as traditionally cast for monolithic integrated circuits (IC) and hybrid microcircuits, may not provide an adequate treatment for the different types of failure mechanisms of a MEMS device. Also, extensions of traditional IC qualification methodologies are perceived as too costly. New approaches need to be developed for devices and packages.

The availability of miniature components has pro-

moted a shift in the way spacecraft are designed. The traditional architecture involves a spacecraft bus connecting several subsystems which themselves consist of individually packaged components. The new architecture aims at eliminating at least one of these levels of integration. Packaging entire subsystems as highly integrated modules eliminates the spacecraft bus entirely in favor of a distributed architecture. Or, embedding active components in structural elements eliminates the component packaging layer.

Ensuring the reduction of life-cycle (i.e., development, qualification, integration, launch, and operation) cost is critical for justification of using MEMS on spacecraft. Incremental reduction in total system mass to reduce launch costs is not a sufficient reason. Miniature conventional technologies (for example, the 25g Litton G2000 and the 77g AlliedSignal Minitact provide 2-axis rate sensing in a hermetic, military-qualified package [3]) exist and raise a question regarding the need to invest in the development of a new technology. The advantages of MEMS lie primarily in the on-chip integration of mechanical and electrical components. MEMS can also provide an increased performance through distributed networks and arrayed sensors. The ability to package these devices and support electronics on a common substrate, significantly reduces mass, power and thermal control requirements of an entire subsystem.

Space qualification of highly integrated modules will rely heavily on processes developed for microelectronics and multi-chip modules (MCMs). However, MEMS have a different set of failure modes requiring unique analyses and tests. Early flight demonstration will be critical for the reduction of qualification costs.

SPACE APPLICATIONS

MEMS sensors and actuators are most commonly considered in the context of either science instruments or inertial guidance, although they can potentially impact spacecraft subsystems such as propulsion, state-of-health monitoring, or active mechanical and thermal control structures.

Science Sensors. Science sensors typically fall into one of two categories, remote sensors (for planetary or astronomical observation at a distance) and *in-situ* sensors (which measure the physical environment surrounding the sensor, including particles and fields). MEMS-based remote sensor elements include infrared focal planes (bolometers, thermopiles, or Golay cells), spectrometers (Fabry-Perot interferometers or gratings), shutters and filters (including microwave filters and resonators), pointing and steering devices, or adaptive optical elements. However, the typical remote sensing platform requires a large aperture, precision pointing and guidance, and the ability to process and transmit large amounts of data. In the foreseeable future, it is unlikely that such platforms will weigh less than 50 kg independent of the MEMS contribution. Therefore the case for MEMS must be made primarily based on performance.

In situ sensors, on the other hand, are often deployed in remote environments under severe mass and power constraints. Since the sensor measures only a very local environment, there is typically an advantage to deploying large number of sensors. Incorporation of MEMS is usually justifiable simply on the basis of size, mass, power consumption, and cost. These sensors cover the entire scope of physical and chemical phenomena involved in the analysis of liquids, solids, gases, plasmas, or fields in free space. A comprehensive review is well beyond the scope of this paper, except to point out that small (<1 kg) autonomous scientific instruments with communication, data handling, power, and rudimentary mobility (the ability to be remotely deployed and to acquire samples) can revolutionize the study of planetary surfaces. Several such instruments are currently being developed, including miniature penetrators deployed directly from space, and puck-sized (10 cm diameter) free-flying magnetometers deployed as a cluster [4].

Guidance Sensors. Spacecraft attitude and position can be determined inertially, optically or by using known fields. A combination of these methods may be needed depending on the various mission phases. Inertial sensors include accelerometers with performance requirements of $1\mu g$ over 0.1-300 Hz and gyroscopes with better than $1^\circ/\text{hr}$ drift rate. Optically, attitude can be determined using star trackers with pitch/yaw accuracy better than 1 arc-sec and roll better than 10 arc-sec, and sun and horizon detectors with better than 1° accuracy. Finally, in satellites orbiting the earth, attitude can be determined using magnetometers with a $0.5\text{-}3^\circ$ accuracy.

Propulsion. Attitude control of deep space vehicles

and orbit maintenance of satellites are traditionally accomplished by a distributed system of thrusters. There are two types of propulsion systems, electric and chemical. The simplest is based on a gas propellant. The implementation of such a system using MEMS is not yet feasible due to the high leakage rates in microvalves. Assuming that no more than 10% of the propellant can be lost during a 5 year mission, the required leakage rate cannot exceed 10^{-6} scc/sec at pressure differentials greater than 1000 psi [5]. Liquid and solid propellant based systems can also be used by evaporating or sublimating the propellant shortly before ejection. Fluid controllers such as valves and regulators are therefore still needed.

Propulsion is accomplished by expanding a gas through a nozzle to increase exhaust velocity. In a micropropulsion system the fluid flow through the thruster throat and nozzle is dominated by boundary layer effects. It is unknown how this condition affects the efficiency of the propulsion system. In addition, the impact of high flame temperatures (on the order of 1000°C) on the structural reliability of the device is also unknown. Several micropropulsion system concepts for ion and chemical thrusters are currently being developed [5,6]. However, advantages over conventional technologies (such as Moog's cold gas thruster/valve unit that weighs 7 grams) will only be realized when many individually-controlled MEMS thruster/valve systems are arrayed to produce the desired total thrust and entire systems (tank, valves, thrusters) are integrated into a single compact unit with minimal transfer of fluid from storage to space.

SPACE ENVIRONMENT

Many MEMS have been developed for automotive applications. In several respects (such as temperature extremes and thermal cycles) the space environment is similar to the environment under the hood of an automobile. Unlike cars, spacecraft also experience severe shock and radiation. Moreover, the conditions greatly vary in different types of missions and different phases within a single mission. Table 1 presents a comparison of the automotive and space environmental parameters. The space parameters given are for the earth-orbiting Space Technology Research Vehicle (STRV-2) mission which will host the MAPLE-2 experiment described later in this paper.

Dynamic Shock. The most severe shock environment is produced during a pyrotechnic separation event of the sort used for deployment or separation of on-board components. The Mars Pathfinder mission has 80 such events scheduled during its 8 month trip to the surface

Table 1: Automotive vs. the Space Environments

Environmental Parameter	Automotive [7]	Space Example: STRV-2 [8]
Operating Temperature	-40°C to +125°C	-25°C to +40°C
Thermal Cycling	> 1,000	> 5,000
Humidity	Up to 100%	35% - 60%
Vibration	15 g, 10-200 Hz	Up to 0.4 g, 20-2000 Hz
EMI Protection	Up to 200 V/m	Up to 70 V/m
Shock	N/A	20 g, 100 Hz 2090 g, 2 - 10 kHz
Radiation	N/A	10 ⁶ rads/year
Depressurization	N/A	1 atm to vacuum at 1psi/sec

of Mars. Traditionally, this shock has been attenuated through the various joints that separate the pyro device from other sensitive components; but as spacecraft shrink in size, the number of joints is expected to be reduced significantly. Although MEMS are more resilient to shock due to the effects of scaling laws, each shock presents an opportunity for an interconnect to fail or for a microcrack to form in an inherently stressed microstructure [9]. Such cracks can grow slowly and eventually lead to failure [10]. A typical shock response spectrum resulting from a small separation nut commonly used in space is shown in Figure 1.

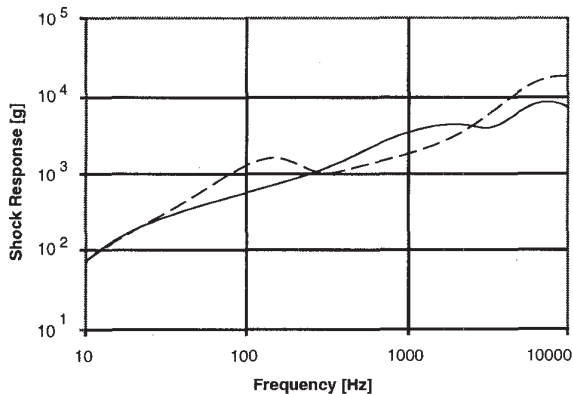


Figure 1: Shock response spectrum 1 foot away from separation nut. Dashed line presents response parallel to the line of separation, solid line presents the response at a 90° angle.

Radiation. The severe radiation environment in space causes various effects on microelectronic systems. Expected radiation levels for earth orbiters, measured in rads (1 rad = 6.25x10⁷ MeV), vary with altitude and

can reach up to 10⁷ rads per year [11]. The radiation issue is complicated by the fact that other factors such as transient effects and dosage rates, in addition to total dose, are important in evaluating impact on microelectronic devices. Recent results of Johnston, et al., demonstrated that greater damage is caused by exposing a device to a specified total dosage at a slower rate than at high rate, calling into question some of the assumption implicit in accelerated life testing [12]. Radiation may impact MEMS devices in three ways:

1. on-board analog and digital microelectronics components of MEMS;
2. the transduction mechanism of the sensor; and
3. mechanical components of MEMS.

Table 2 presents the expected physical impact of each type of damage caused by radiation [13]. Note that this table presents potential impact on aspect (1) above. Research into radiation impact on aspects (2) and (3) is in progress. Mitigation of these effects require fundamental understanding of the resulting failure mechanisms. Shielding approaches alone not only add a weight penalty to a MEMS/electronics assembly, but are effective only against total ionizing dose.

Table 2: Potential Impact on MEMS Due to Radiation

Radiation Effect	Physical Impact
Ionization damage (electrons, protons)	Charge trapping, interface state growth at oxide-silicon interfaces
Single Event Upset (protons, high energy ions)	Deposition of electron-hole pairs by particle-induced current pulse
Single Event Latchup (protons, high energy ions)	Localized, self-sustaining high current condition in semiconductor materials
Single Event Hard Error (protons, high energy ions)	Localized charge deposition resulting in a permanent effect
Single Event Burnout (high energy ions)	Breakdown of large voltage across thin oxide
Displacement Damage (neutrons, protons)	Displacement of lattice atoms; minority carrier lifetime, doping level effects

PACKAGING AND QUALIFICATION

Packaging techniques for MEMS borrow heavily from those developed for microelectronics. Similarities include hermeticity and chip-level integration techniques such as MCMs. Differences include a unique set of failure modes due to the mechanical nature of

MEMS that are still not very well understood. In the absence of comprehensive device and failure simulation tools, we need to develop reasonable qualification practices for MEMS devices. These practices need to be based on real properties of these devices, and not on extrapolated failure modes for electronic circuits.

Efficient Packaging. Packaging technologies involve the mechanical and electrical structures used to combine components to form a system. Packaging is hierarchical in nature, reflecting convenient breakpoints in technology feature sizes and processes. Much of the bulk in electronics systems is due to packaging. In conventionally packaged systems, more than 99% of the structure is directly related to packaging, and with MCMs, the fraction is only slightly improved (90-95% in most cases). Through the use of 3-D packaging and chip-level devices it is possible to improve volumetric efficiency and dramatically reduce size and weight.

Most space parts are hermetically sealed due to a perceived increase in reliability and to minimize potential outgassing. Outgassing is a concern since particles could redeposit onto optics, solar cells, and instruments. By employing more advanced two- and three-dimensional packaging approaches, a systematic reduction in the surface area that might contribute to outgassing can be achieved.

Space Qualification. Verifying reliability ideally involves understanding failure modes in a hierarchical sense and establishing a means of systematically eliminating their likelihood over the desired product life. The understanding of failure modes is usually based on experience with similar assemblies or elements, a strategy that is often not applicable to a new technology such as MEMS. Once the most important failure modes of a technology are identified, they are reconciled against the likely environmental conditions associated with the mission or product life. If the technology proves to be sufficiently robust, failure modes are aggravated by subjecting assemblies or elements to similar conditions, usually in some "accelerated" or more intense manner.

In practice, developers apply sets of test methods, chosen from a palette, such as the military standard MIL-STD-883 (Test Methods and Procedures for Microelectronics Users). To avoid the effort of developing custom qualification specifications for each new technology, it has often been the habit of space systems designers to insist upon compliance to a pre-ordained set of test methods in blanket fashion, such as those prescribed by MIL-H-38534 (general qualifications of hybrid microcircuits). However, newer MCM, three-dimensional packaging, and MEMS technologies pos-

sess traits which do not permit casual simplification of the reliability evaluation and assurance processes. More flexible compliance strategies are required, such as qualified manufacturers' line (QML) approaches, which focus on the quality of the process through which assemblies are created, instead of relying on the results of the screens alone. In some cases, QML permits screens to be eliminated partially or completely.

FLIGHT EXPERIMENT

The lack of flight heritage is a major impediment to the use of MEMS devices in space. While ground testing and other qualification techniques can assure the reliability of a device or an assembly, its space "worthiness" is not proven until it has flown in space. An early flight demonstration of a MEMS package is currently being developed cooperatively by Phillips Laboratory (PL) and the Jet Propulsion Laboratory (JPL). It is designed as an experiment in the electronics testbed (ETB) on board the Space Technology Research Vehicle-2 (STRV-2, a joint U.K./U.S. mission). In 1997, it will be launched into a highly elliptical orbit, providing an unusual opportunity to explore the impact of harsh space environmental effects.

The experiment, Microsystems and Packaging for Low Power Electronics II (MAPLE-2), includes the integration of three Analog Devices ADXL02, three ADXL05 microaccelerometers and a single tunneling microaccelerometer developed at JPL [14]. These particular sensors were chosen to evaluate radiation effects on commercial MEMS components as well as to compare the performance and space survivability of two different types of transducers, capacitive and tunneling. The sensors are housed in a low-mass (< 1.5 lbs.), low-power (< 1.5 W) package that has a microcontroller-based data acquisition system. The experimental configuration provides in-situ monitoring capability for operating the accelerometers in a self-test mode, as projected satellite on-orbit accelerations may fall below measurement resolution.

MAPLE-2's purpose is to evaluate the performance of commercial capacitive accelerometers and a tunneling accelerometer in the harsh space environment. It is expected to experience more than 5,000 thermal cycles, each correlating with a 90-minute orbital period. Temperature extremes are expected to be -25°C and +40°C and maximum total radiation dose is projected at upwards of 50,000 rads.

The MAPLE-2 block diagram is shown in Figure 2. Power conversion of a single 28 Vdc input to +5, ±15 V, and +115 V is performed with custom conversion circuitry. The sensed accelerations of each accelerome-

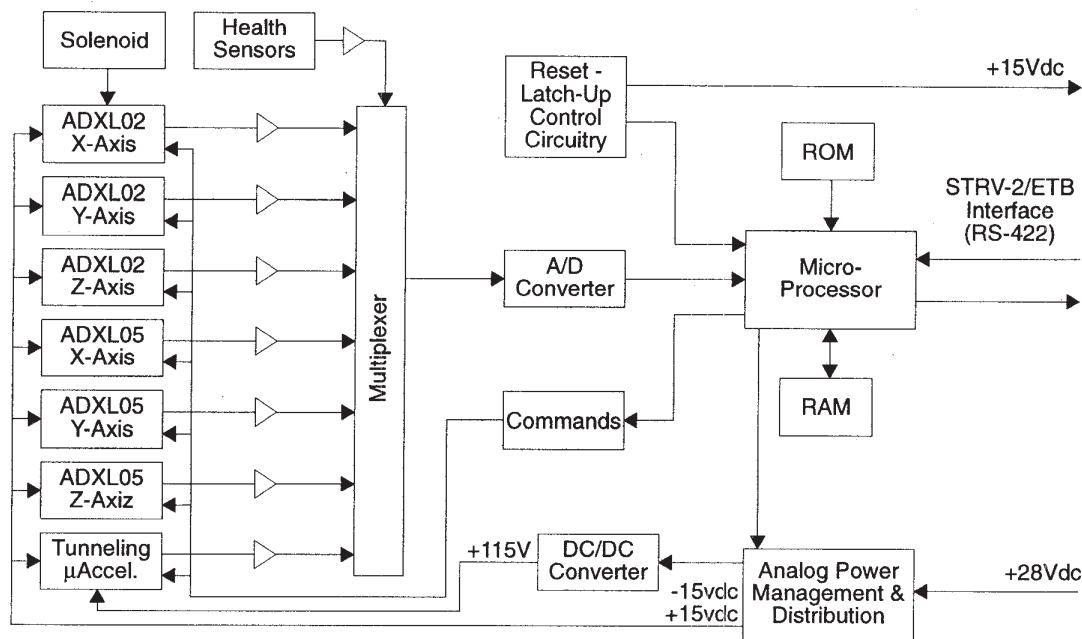


Figure 2: Schematic diagram of the MAPLE-2 flight experiment.

ter are scaled and multiplexed to an Analog Devices AD7572 12-bit analog-to-digital converter (ADC). This low-power ADC has been found in a customer test to be tolerant to 15-25 krad total dose. The central processor in this case is a radiation-hardened 8051 "clone," which operates from a hardened 2Kx8 Harris PROM and 8Kx8 hardened SRAM (based on a SIMOX process which is no longer available). Other small scale analog and digital components were selected based on availability in a tested radiation hardened format.

Since the STRV-2 acceleration environment is projected to be nominally very "quiet" once the satellite is in orbit, an artificial acceleration stimulus is provided to the MEMS devices through an on-board solenoid. The 5g solenoid provides a direct mean of "injecting" known test impulses up to 30 mN that allow performance degradations to be more accurately assessed. The timeline of a single experiment cycle is shown in Figure 3. At the end of each cycle, MAPLE idles until the host controller requests a download of signature information. The completion download signifies the end of the MAPLE experiment cycle, which is to be performed nominally 4 times per 90-min orbital period.

Conventional packaging techniques are used for MEMS devices and support electronics in MAPLE-2, due to scheduling constraints. As such, this MAPLE experiment serves more importantly as a testbed for MEMS devices in space orbit as opposed to a true demonstration of the extreme miniaturization possible through exploitation of MEMS and MCM technolo-

gies. MAPLE-1, a low-orbit precursor experiment, provides a simple packaging reliability experiment to examine parametric degradations that might occur with new packaging technologies in space. Future MAPLE experiments will provide the opportunities to further augment a building database on MEMS and packaging.

Before the MAPLE-2 experiment will be integrated into the STRV-2 spacecraft, it must go through a regimen of thermal, vibration, and electromagnetic interference qualification testing. The required environmental tests are given in Table 3. Radiation performance testing of accelerometers and experiment assembly will be conducted at PL through its Co₆₀, Cs₁₆₁, flash X-ray, and low energy X-ray radiation sources. These tests are designed to uncover gross design faults and subsystem incompatibilities.

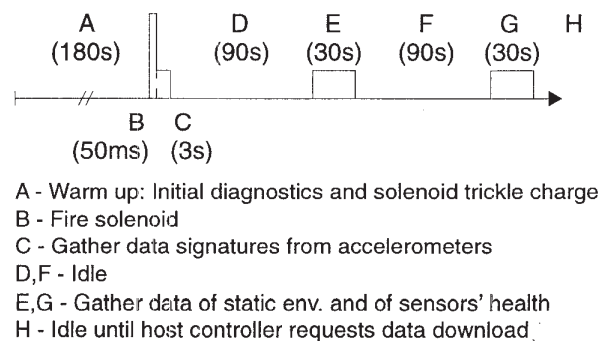


Figure 3: Timeline of the MAPLE-2 flight experiment.

Table 3: STRV-2 Required Environmental Tests for Flight Experiments

Environment	Required Test Levels
Radiation	Total ionization dose: 10 krad Single event effects: No latchup or dielectric rupture at LET ^a < 60, No gate rupture at LET < 26, No upsets at LET < 37
Dynamic: Random Vibration	Up to 0.3 g/√Hz over 20-2000 Hz in each of 3 axes for 3 minutes
Dynamic: Shock	None, shock test will be performed on the integrated ETB.
Thermal	2 cycles of +65°C to -45°C in vacuum
EM Compatibility	None, tests will be performed on the integrated ETB.

a. Linear Energy Transfer in charge deposited per unit path length divided by density (MeV cm²/g)

SUMMARY

MEMS provide a significant reduction in size and mass of scientific, remote sensing, and communication space vehicles. While this will reduce the cost of the launch phase, it may not reduce the total life cycle cost. The cost of developing packaging and qualification methods to ensure reliability in the harsh space environment can only be justified for technologies that significantly increase performance or enable new functions not possible with conventional technologies. MEMS can revolutionize the way spacecraft are currently designed and built by enabling new architectures based on *in-situ* sensors, distributed sensors and actuators, and dense electronic packaging. To accelerate the space qualification process, we are conducting ground experiments and developing the first of many flight validation experiments.

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