

# **MEMS for pico- to micro-satellites**

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## **ABSTRACT**

MEMS sensors, actuators, and sub-systems can enable an important reduction in the size and mass of spacecrafts, first by replacing larger and heavier components, then by replacing entire subsystems, and finally by enabling the microfabrication of highly integrated picosats. Very small satellites (1 to 100 kg) stand to benefit the most from MEMS technologies. These small satellites are typically used for science or technology demonstration missions, with higher risk tolerance than multi-ton telecommunication satellites. While MEMS are playing a growing role on Earth in safety-critical applications, in the harsh and remote environment of space, reliability is still the crucial issue, and the absence of an accepted qualification methodology is holding back MEMS from wider use. An overview is given of the range of MEMS applications in space. An effective way to prove that MEMS can operate reliably in space is to use them in space: we illustrate how Cubesats (1 kg, 1 liter, cubic satellites in a standardized format to reduce launch costs) can serve as low-cost vectors for MEMS technology demonstration in space. The Cubesat SwissCube developed in Switzerland is used as one example of a rapid way to fly new microtechnologies, and also as an example of a spacecraft whose performance is only possible thanks to MEMS.

**Keywords:** MEMS, spacecraft, satellites, nanosatellites, cubesats, space

## **1. OVERVIEW OF MEMS APPLICATIONS IN SPACE**

In 2008 the market for MEMS (MicroElectroMechanical Systems) devices was nearly \$8 Billion according to Yole Développement [1]. MEMS encompass an enormous range of applications, from RF switching to projection display to inertial sensors to implantable pumps. Combining low mass, low power consumption, small volume and possible integration with control and sense electronics, MEMS seem ideal for space applications, where it costs approximately 10'000 \$ to place one kg in low Earth orbit (LEO).

Reliability is a key concern for spacecraft, in view of the very larger development costs, near impossibility of repair (the service missions to the Hubble Space Telescope are the notable exception), and limited launch slots. One major difference between operation on Earth and in Space is the radiation level [2]. Other space-specific reliability concerns are thermal cycling and thermal shocks, vibration and mechanical shock at launch and stage/heat shield separation, and operation in very high vacuum. The typical service life of a telecommunication satellite is 15 years, during which time the spacecraft must operate continuously and flawlessly. For this reason, and because of the need for radiation tolerance, new technologies are generally accepted in space applications only many years later than in consumer electronics, except for cases where a new technology is required for a mission, or allows dramatic performance enhancement or mass reduction. This was the case for instance for FPGAs and is now the case for MEMS.

The fraction of the \$8 Billion MEMS market for space is very small, and MEMS for use in space often have unique requirements. MEMS have been proposed for a number of space applications, as lighter and smaller replacement parts or as entire new systems [3][4][5], or as a means to provide affordable redundancy and hence improved operational reliability [6]. Few MEMS components have been flown in space. MEMS for space are currently either commercial off-the-shelf (COTS) parts such as accelerometers or gyroscopes that have been subjected to additional testing and qualification, or new MEMS devices that are crucial enabling technologies for science missions which cannot proceed without MEMS (such as the AFM on the Phoenix mission on Mars [7]). In the medium term MEMS technology will allow sub-systems (such as attitude determination, phased array antennas, Earth sensors, optical switches, low-thrust

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propulsion systems) to be reduced significantly in size and mass. In the longer run MEMS can enable new classes of extremely small, intelligent, self managing and relatively low-cost batch-produced picosatellites operating in constellations. Most MEMS devices currently under development for specific space applications are not intended for picosatellites, principally because most satellites currently have masses larger than 100 kg. However pico and nanosatellites are the main users in space of COTS MEMS parts (pico and nanosats are also the main users in space of COTS microcontrollers, batteries, etc since the development budget of these small satellites often precludes using standard space grade components). Some of the more developed MEMS areas for space are listed below, and can also be found in [8].

*Inertial Navigation:* accelerometers and gyroscopes are the most mature MEMS devices used in space, used to instrument launchers as well as rovers on Mars. Since these devices are available as COTS parts for commercial and military applications, it is likely that they can be re-qualified for space by de-rating (for one de-rating procedure see ref [14]). There have been several studies addressing COTS accelerometers for space [11][12][13]. COTS accelerometers have been shown to survive 1000 temperature cycles from -65°C to +150°C, as well as 30,000 mechanical shocks of 2,000 G. To measure microgravity on the GeneSat1 mission, model 1221 capacitive micromachined accelerometers from Silicon Designs Inc., Issaquah, WA, USA were flown in 2006 in low Earth orbit [15].

*RF Switches and Variable Capacitors:* MEMS technologies enable the fabrication of very compact low-loss RF switches, as well as capacitors with a large tuning range. Such devices are just starting to be commercially available, for example from Radant MEMS [16] (Stow, MA, USA). RF switches were flown in space on the OPAL Picosats in 2000. They were stored in orbit for a year, and then successfully operated [17]. IMEC, in Leuven, Belgium, have led several studies into the reliability of RF MEMS for Space [18].

*Atomic Force Microscope:* an AFM was one of the scientific instruments on the 2008 Phoenix mission to Mars [7][19]. The piezoresistive single crystal silicon based AFM operated flawlessly on Mars. The scanner and cantilevers of the AFM were not radiation hardened but its control electronics were. This is a good example of rapid acceptance of MEMS in space. The near-impossibility of making an AFM without MEMS technology, and the fact that a failure of the AFM would not compromise the mission, allowed MEMS technology to be much more readily accepted.

*Bio and Microfluidics:* SU8 and other polymers, as well as Pyrex and silica can be used to fabricate micro-fluidic devices, including channels, nozzles and pumps. Such devices are principally being developed for medical or pharmaceutical (lab-on-a-chip) applications, and have been flown on the 25 cm long GeneSat1 in 2006 to study the development of E. Coli cells in microgravity [15] [31] as well as in a small micro-reactor for yeast cell studies on the Space Shuttle and could also eventually be used as part of a propulsion system.

*Bolometers:* micromachining allows thermal isolation of small detectors, enabling both uncooled and cooled bolometer arrays to offer very high performance. Such devices are commercially available for earth-based IR detector applications. A MEMS bolometer from JPL/Caltech [10] is planned for the ESA/NASA Planck mission in 4-2009 to image the anisotropies of the Cosmic Background Radiation Field.

*Optical instrumentation:* the NIR-Spec (Near InfraRed Spectrometer) on the James Webb Space Telescope (JWST) will use MEMS-based micro-shutters manufactured by NASA/GSFC, whose radiation testing at 60 K is reported in [20]. The JWST is expected to be launched in 2013. The MEMS-based microshutter allows important performance improvement and several orders of magnitude mass reduction compared to a conventionally mechanical shutter array.

*Optical Switching and Communication:* The boom in optical MEMS between 1999 and 2002 led to the development of large optical switch matrices based on MEMS devices. There are ongoing European Space Agency (ESA) projects on the development and qualification methodology of such MEMS switches for space. There have been studies of COTS parts [21], but no devices have been flown.

*Louvers for thermal control:* MEMS louvers were developed by the Johns Hopkins University and NASA using a polysilicon process, allowing the emittance of the spacecraft to be varied [22]. Launched in 2006 aboard NASA's Space Technology 5 (ST5), they successfully operated as predicted.

*Propulsion:* MEMS propulsion systems produce low thrust, from  $\mu\text{N}$  to at most 1 N. Such thrust levels can allow orbit maneuvers for small satellites, or attitude control and station keeping for larger satellites. There are several approaches to using MEMS for propulsion in space, reflecting the different propulsion technologies such as cold gas, hot gas, and electric propulsion. Electric propulsion allows reducing the amount of propellant required due to the high propulsion

efficiency, but requires enough solar power to extract and accelerate the ions, often more power than available on very small satellites.

One approach to miniaturizing an ion-thruster is to micromachine and integrate the electron source, gas handling, nozzle and other components, is reported in [23]. Another approach to integrated MEMS colloid thrusters is described in [24][25][26], where arrays of micromachined ion sources using ionic liquids as fuel are used to create highly modifiable thrust. Yet another approach is to microfabricate arrays of explosive microthrusters which consist of micromachined cavities filled with solid propellant. A micromachined hotplate is bonded on top of each cavity to allow ignition of the microthrusters one at a time [27][28]. Finally, silicon machining has been used to fabricate compact cold gas thrusters consisting of bonded Si chips to form a reaction chamber and compact nozzle [29]. A good overview of micropropulsion for Cubesats can be found in [30]. A Cold Gas Microthruster (CGMT) from Marotta Scientific Controls was flown on NASA's ST5 mission. More highly integrated cold-gas thrusters are expected to be flown in 2009. Formation flying missions such as NASA & ESA's Laser Interferometer Space Antenna (LISA) planned for 2019 may well use MEMS-based micro-propulsion.

MEMS Device	Flown? (mission)	Estimated TRL of the MEMS for Space applications
Inertial Navigation (accelerometers, gyroscopes)	Yes, almost routinely for NASA	High
Pressure sensor	Yes, routine for launch vehicles	High
Magnetometer	Yes (Cubesats)	High
AFM (atomic force microscope)	In 2008 (Phoenix)	Medium- High
Sun sensor	In 2008 (Delfi 3C)	Medium - High
Micro-fluidics	Yes (3x Shuttle, and Genesat)	Medium
Bolometer	In 2009 (Planck)	Medium
Optical switching	No	Medium
Propulsion (ion, cold gas, colloid, solid propellant)	In 2006 (ST5)	Medium
Thermal control	In 2006 (ST5)	Medium
RF switch and variable capacitor	In 2000 (OPAL picosats)	Low -Medium
MEMS oscillator	No	Low - Medium
Adaptive optics and MOEMS-based optical instruments	No, planned for James Webb Space Telescope (2013)	Low - Medium

Table 1: Summary of which MEMS technologies have been flown, and rough estimate of Technology Readiness Level (TRL).

## 2. CUBESATS, PICO AND NANOSATELLITES

The generally accepted definition [32] for pico-satellites is a spacecraft with a wet mass (i.e., mass including propellant) of 1 kg or less, nano-satellites have mass between 1 and 10 kg, and micro-satellites range from 10 to 100 kg. For comparison, a typical telecom satellite in Geostationary orbit (GEO) has a mass of 1000 to 5000 kg.

Large satellites have long development times, of order 5 to 15 years. Smaller satellites can be developed much faster. Picosatellites and Nanosatellites are natural users of MEMS because they require very high levels of integration and miniaturization in order to fit data handling, communication, attitude determination and control, payload, structure, batteries and other subsystems in such a small volume. A short overview of recent pico and nanosatellites is given below.

The Cubesat standard was defined in 1999 at the California Polytechnic State University, San Luis Obispo, CA and at Stanford University's Space Systems Development Lab, Palo Alto, CA, as a means to provide affordable access to space, initially primarily for academic institutions. Cubesats are cubic satellites 10 cm on a side, with a mass of up to 1 kg. Detailed specifications can be found at [33]. Cubesats can also be built in a "triple" standard, 10 x 10 x 30 cm<sup>3</sup>, maximum mass of 3 kg. Single Cubesats are typically launched in groups of three, and Cubesats are generally "piggy-back" launches: the main customer of the launch vehicle chooses the orbit for its conventional-size satellites; once those main spacecraft are in orbit, the Cubesats are ejected from the launcher in a slightly different orbit to avoid any collision. There are no dedicated Cubesat launchers. Several companies offer Cubesat launch services, freeing the Cubesat builder from negotiations with the various launch providers as well as taking care of export control procedures.

There are currently approximately 80 Cubesats under development, and 40 have been launched from a variety of American, Russian, Japanese, and Indian launch vehicles. The field is active, with 5 small companies offering kits and parts specifically for the Cubesat standard [34]. While Cubesats serve in large part to teach students about system engineering and about space systems, they are also ideal vehicles for proving in or testing novel technologies that are not yet acceptable for larger commercial missions because of a lack of flight history. It is a reasonable approach to use missions which can accept large risk (such as Cubesat missions) to prove in novel technologies, or to provide the first demonstration of space application of a technology that has been shown to be reliable on Earth. The main limitation of using Cubesats or other nanosats to increase the Technical Readiness Level (TRL) of MEMS components is the generally short life (less than 1 year typically) of these small satellites, which precludes learning how a MEMS device degrades after many years in space.

For cost, lead time and availability reasons, Cubesats are generally built using commercial components, not space qualified or radiation tolerant parts. While using such parts may reduce the lifetime of Cubesats, it also means they are flying very recent technologies. The reliability of MEMS for space is discussed in [9][35] and the radiation sensitivity of MEMS to radiation is reviewed in [8]. Despite their lack of radiation shielding, radiation is generally not a major concern for Cubesats and most nanosats because they operate in low-Earth orbit, and have a lifetime probably limited by the degradation of their rechargeable batteries rather than the 3 to 15 krad they will receive per year.

The use of MEMS in Cubesats has focused on their use in the attitude determination subsystem: inertial sensors (gyroscopes), magnetometers, and optical sensors such as sun sensors and star trackers. Magnetometers and gyroscopes are typically COTS devices, while sun sensors and star trackers are space specific developments. These are presented in the following section.

There are several nanosatellites in orbit. For example, the OPAL 13.5 kg satellite launched in 2000 held two picosats, each with an RF MEMS switch from Rockwell Scientific on board. The two picosats were ejected once OPAL was in orbit. One goal was to observe how MEMS devices could operate after storage in space. The picosats were turned on after one year in LEO orbit, and operated correctly [17].

MEPSI, a MEMS-based PICOSAT inspector, is a series of picosats developed by Aerospace Corp for DARPA, and have been launched in tethered pairs from the cargo bay of the Space Shuttle on flights STS -113 in 2002 and STS-116 in 2006. They have a combined mass of 3.5 kg, and dimension of 10 x 10 x 12.5 cm<sup>3</sup>. The ones flown in 2006 have a 5 thruster cluster system using a MEMS pressure transducer. Figure 1 is a NASA photo showing two tethered MEPSI satellites being launched from the Shuttle cargo bay.

NASA's Space Technology 5 (ST5) was a set of three 25 kg spacecraft, launched in 2006, that operated as a constellation and demonstrated several new technologies, including the MEMS louvers mentioned above, and a cold gas thruster using MEMS components.



Figure 1. Two MEPSI nano-satellites just after ejection from the cargo-bay of the Space Shuttle on mission STS-116 in December 2006. Photo credit: NASA.

### 3. MEMS-BASED ADCS ON CUBESATS

The Attitude Determination and Control System (ADCS) is the subsystem where MEMS are playing the biggest role in Cubesats, because MEMS sensors offer high performance, high reliability, and low-power consumption, and because this is field where highly reliable commercial devices are available at low cost (a few dollars per axis for accelerometers, less than \$100 for gyroscopes). Propulsion (which may be part of the ADCS system if the propulsion serves to orient the spacecraft) is also an active field.

The University of Illinois's dual-cube cubesat ION (Illinois Observing NanoSatellite) included a microvacuum arc thruster ( $\mu$ VAT) [37]. The system consists of 4 micro-thrusters allowing two-axis rotation. Sadly ION was destroyed along with 11 other Cubesats when the launch vehicle exploded in 2006 only 86 seconds after lift-off.

Delft University in the Netherlands is planning to fly a MEMS-based cold gas thruster developed by TNO, TU Delft, and U Twente on its triple-format (3 liter volume) Cubesat Delfi-n3Xt [38], with launch planned for 2010. Here the MEMS technology (nozzles, valves) and cold-gas generation allows very important mass and volume reduction, enabling a Cubesat to have propulsion, thus greatly increasing the range of missions which Cubesats can carry out.

A good example of the use of commercial MEMS devices on a Cubesat is the Danish Cubesat AAUSAT-II, launched in 2008, carrying 6 Analog Devices Single Chip Yaw Rate Gyroscopes (model ADXRS401), and one 3-axis magnetometer model HMC1053 from Honeywell as part of the attitude determination system. The sensors operated as expected in orbit.

SwissCube [39] is a Cubesat developed in Switzerland, lead by the EPFL Space Center, with launch planned for March 2009. It will image the atmospheric airglow, which is light emitted most strongly at 762 nm from an oxygen layer 85 km to 100 km in altitude, as illustrated in Figure 2. To take pictures of the airglow, SwissCube must be pointed at the limb of the Earth, and requires attitude determination accurate to better than  $1^\circ$ . The only way to obtain the required performance within the mass, volume and power budgets was to use MEMS components. The goal is not to prove the MEMS components for their own sake, but rather MEMS are unavoidable for SwissCube because high-performance attitude determination on Cubesat missions is only possible with MEMS technology.

The MEMS gyroscope selected for SwissCube was the ADXRS614 from Analog Device because of its low power consumption and a high sensitivity for low rotation rates. The gyroscopes are needed principally during eclipses (approximately 30% of each orbit is in eclipse). Three gyroscopes are mounted at  $90^\circ$  to each other, one on the main ADCS printed circuit board, and two on smaller board mounted perpendicularly to the ADCS board, as shown in Figure 3.

The same 3-axis Honeywell magnetometer (model HMC1053) was selected as for the AAUSAT-II mission. Knowing the position of the satellite in its orbit, and the local vector of the magnetic field allows the determination of the relative orientation of the satellite with respect to the Earth.

When SwissCube is not in the shadow of the earth, the attitude determination system is completed by another set of MEMS sensors, micromachined Sun sensors developed and fabricated at the Danish Technical University (DTU). Very similar sun sensors, also from DTU, were flown on the Danish Cubesat DTUSat1 in 2003. Unfortunately DTUSat1 did not operate in orbit for reasons that could not be determined. These sun sensors are photodiodes with micromachined slits that each provide two analog output currents, each proportional to one of the two angles between the plane of the sun sensor and the vector to the sun [40]. Six sun sensors are used, one on each face of the spacecraft, as shown in Figure 4. If the position of the sun with respect to the Earth is known (e.g. from the time and from the orbit parameters), the orientation of the satellite with respect to the Earth can be readily obtained from the angle of one satellite face to the sun vector.

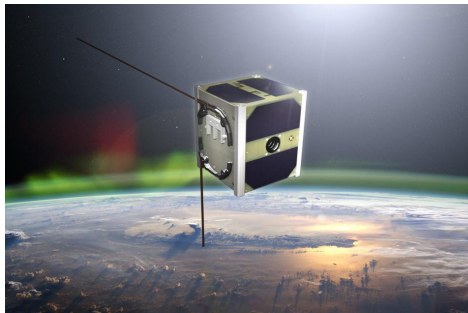


Figure 2: Artist's impression of SwissCube in orbit. The airglow can be seen at the green arc above the Earth.

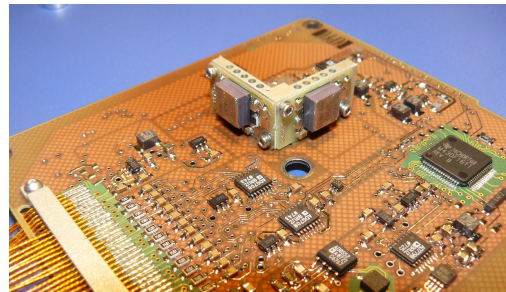


Figure 3: part of the ADCS board on SwissCube. The perpendicular mounts for the two of the three MEMS gyroscopes are clearly visible.

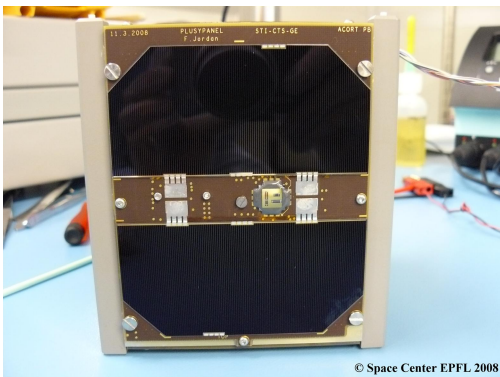


Figure 4: One side of SwissCube (10x10 cm<sup>2</sup>). At the center of each face, between the top and bottom solar panels, the MOEMS sun sensor from DTU can be seen (just to the right of the central hole)

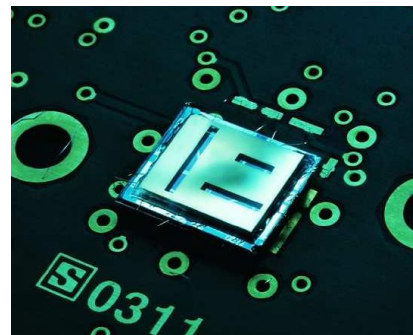


Figure 5: Optical micrograph of one of DTU MOEMS 2-axis sun sensors [DTU]

### CONCLUSIONS

MEMS technologies are increasingly used in space. They are routinely flown in Cubesats, small 1 kg satellites, where high levels of risk are accepted, and because operation without MEMS entails enormous performance penalties for such



small and highly integrated systems. The attitude determination subsystem is currently the part of the pico and nanosatellites that is based on MEMS sensors. Future Cubesats will rely even more heavily on MEMS technology.

Picosatellites and nanosatellites have much smaller mass and power budgets than large multi-ton commercial satellites, and hence, along with scientific satellites, are the early adopters of MEMS in space. Scientific missions are starting to accept to MEMS components, both because of their high performance, as well as because of important mass and power savings.

MEMS qualification procedures and radiation-tolerant control electronics for MEMS are progressing quickly, and need to mature further before MEMS solutions are widely accepted in commercial spacecraft.

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