MEMS for Space

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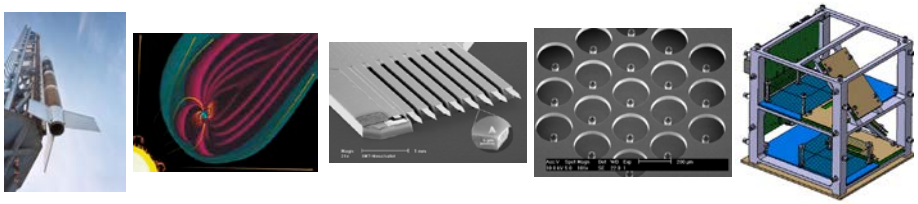


MEMS for Space

- Introduction to satellites
- Why MEMS for space
- Reliability aspects (short overview)
- Examples of MEMS in space:
  - RF MEMS
  - AFM on Mars
  - Earth sensor
  - Micro-propulsion
- SwissCube

"Exam questions"

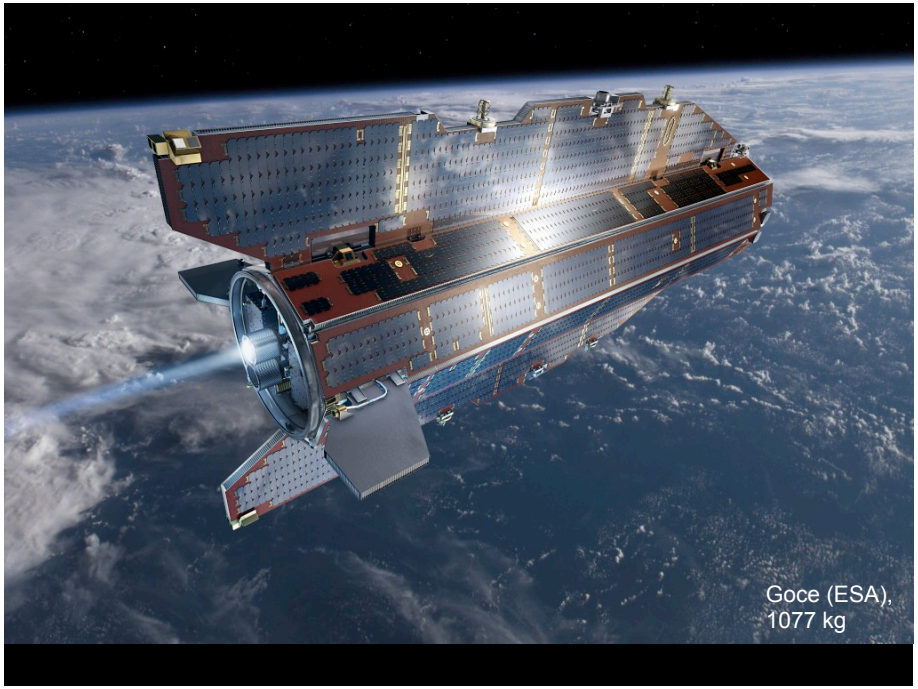
- **1. Why are MEMS not widely used on satellites, despite their small mass and functionality?**
- **2. Summarize the effects of radiation on MEMS, and comment on whether this is a problem for most missions.**

Satellites

- Mass usually a few tons
- Lifetime approx 15 years
- to date, 4600 launches for over 6000 satellites, of which approx 800 are operational

Two main orbits:
- Low Earth Orbit (LEO): 200-1200 km altitude
- Geostationary (GEO): 36'000 km altitude

Satellite ESA Envisat, launched 2002



Key satellite elements

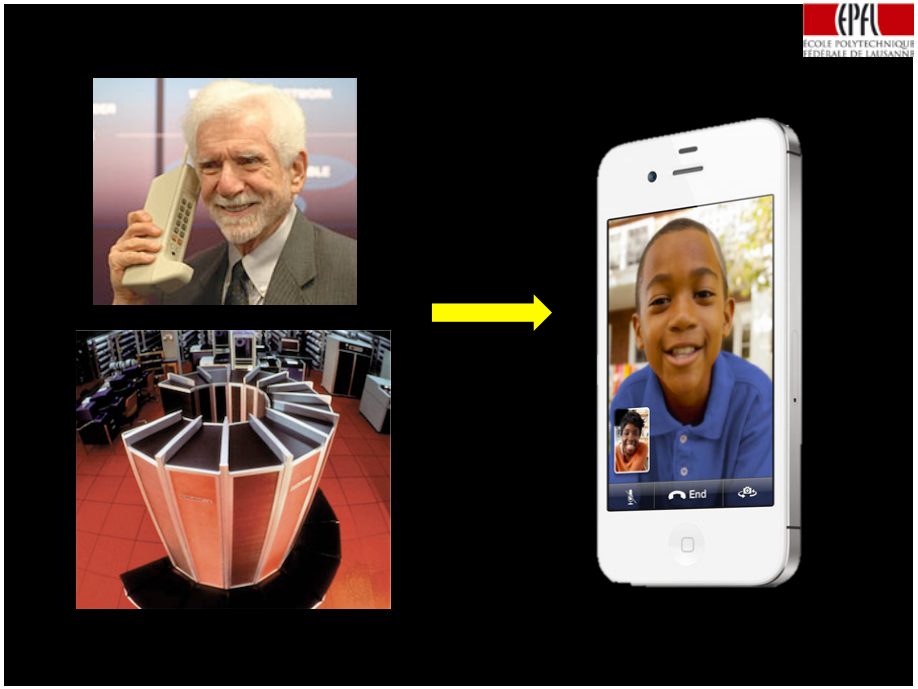
- Structure
- Propulsion
- On-board computer
- Batteries
- Antennas
- Solar cells
- Payload

Launch vehicles

- Must reach> 7.9 km/s (28'400 km/h)
- Vibrations!
- Rapid temperature change
- From pressure of 1 atm. to high vacuum in 1 minute…
- For Indian PSLV
  - In 2 minutes, altitude of 60 km, speed 6000 km/h
  - In 4 minutes, 220 km and 13'000 km/h
  - After 15 minutes, in orbit at 650 km

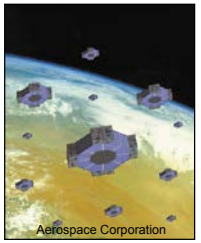
Why MEMS / microsystems ?

- **Increased functionalities compared to ICs with sensing and actuating functions**
- **Compared to other technologies:**
  - Some physical phenomenon benefit from the scaling effect
  - Possibility to realize smart devices with the integration of signal processing
  - Smaller / higher integration, low-power
  - Batch fabrication process / lower cost



Why MEMS for space?

- **Satellites / Spacecraft**
  - Launch cost typically $10,000/kg for LEO (low earth orbit)
    >100 M$ for 5 ton satellite in GEO (geostationary)
  - Mass and volume are extremely limited
  - Can't go and repair it!
- **MEMS advantages include:**
  - **Very low mass & very small volume**
  - Low power consumption
  - Can be highly resistant to vibration and shock
  - Can be radiation hard
  - Integration with drive/control electronics
  - Vast range of functionality, multi-functional materials



➢ **MEMS technologies are excellent fit for space applications, especially for small (1 to 100 kg) satellites**

➢ **But must demonstrate reliability: space is a very conservative industry**

Attributes of MEMS?

Many fields:

- RF (switch, tunable inductance and filter)
- Bio (reactor, DNA analysis)
- Optical (switch, tunable laser, adaptive optics)
- Inertial (accelerometer, gyroscopes)
- Sensing (AFM probes)
- Propulsion and Power
- Atomic clocks, frequency standards…

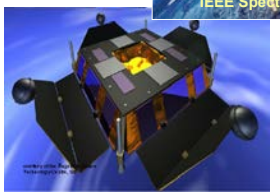
MEMS as an enabling technology in space

- Today MEMS can start **replacing larger components**, such as:

  accelerometers, sun sensors, RF filters, RF and optical switches, ion and chemical propulsion…

- Then with MEMS, one can go much further with **highly-integrated MEMS-based picosatellites**

  - Arrays of pico-satellites for weather prediction, or communication, space science…
  - "Inspector" satellites piggy-backed on larger satellites



Focus on small satellites

MEMS used in big missions when:

1. Cannot do without (e.g. AFM on Mars)
2. Adds zero risk, as failure does not jeopardize mission (AFM on Mars)
3. Adds significant benefit; e.g., shutter arrays on JWST (Hubble space telescope successor)

MEMS used in small satellites: for now as demonstration, or using COTS parts (Gyro)

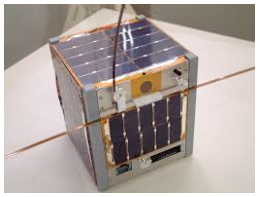
ESA, NASA, JAXA are all funding research into using MEMS for space, both:
- for specific missions
- as generic enabling technology: Qualification? Radiation?

Satellite Classification

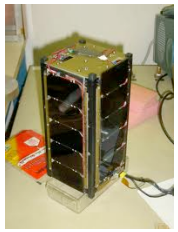
Group name	Wet Mass
Large satellite	>1000kg
Medium sized	500-1000kg
Mini satellite	100-500kg
Micro satellite	10-100kg
Nano satellite	1-10kg
Pico satellite	0.1-1kg
Femto satellite	<100g

Cubesat!

About 40 have been launched, 80 under construction
Standard format: 1 kg, 1 liter (or 3 kg 3 liters)



University of Tokyo CubeSat



University of Illinois - ION Cubesat Project

Bob Twiggs

Image credit: NASA

MEPSI deployed from space shuttle

Technical readiness Levels (NASA)

TRL1	Basic principles observed and reported	Low
TRL2	Technology concept and/or application formulated	
TRL3	Analytical and experimental critical function and/or characteristic proof-of-concept	
TRL4	Component and/or breadboard validation in the laboratory environment	Medium
TRL5	Component and/or breadboard validation in the relevant environment	
TRL6	System/subsystem model or prototype demonstration in the relevant environment (ground or space)	
TRL7	System prototype demonstration in a space environment	High
TRL8	Actual system completed and flight-qualified through test and demonstration (ground or flight)	
TRL9	Actual system "flight-proven" through successful mission operations	

MEMS in Space
(a slightly euro-centric perspective)

MEMS Device	Flown? (mission)	Estimated MEMS TRL (for space)
Inertial Navigation (accelerometers, gyroscopes)	Yes, almost routinely for NASA and on cubesats	High
Pressure sensor	Yes, routine for launch vehicles	High
Magnetometer	Yes (Cubesats)	High
AFM (atomic force microscope)	In 2008 (Phoenix)	Medium- High
Micro-fluidics	Yes (3x Shuttle, and Genesat)	Medium – High
Sun sensor	In 2008 (Delfi 3C)	Medium
Bolometer	In 2009 (Planck)	Medium
Adaptive optics and MOEMS-based optical instruments	No, but planned for James Webb Space Telescope (2018)	Medium
Active Thermal control	In 2006 (ST5)	Medium
Propulsion (ion, cold gas, colloid, solid propellant)	In 2006 (ST5) 2010 (PRISMA)	Low - Medium
RF switch and variable capacitor	In 2000 (OPAL picosats)	Low -Medium
MEMS oscillator	No	Low
Optical switching	No	Low

MEMS in space

- **What is there now?**
  Many MEMS devices planned and being developed, but hardly anything is on orbit! And nothing on large satellites…
  - RF switches on two picosats inside Stanford's OPAL
  - Accelerometers and Gyros
  - A few technology demonstration missions
- **Much planned, but little flown. Why?**
- **Qualification for space lengthy**
  - How to qualify a MEMS device for Space? The same issue was raised when commercializing MEMS for automotive, telecom, displays:
    - How to qualify MEMS for space use if it is a new and unique device (i.e., very small sample size)
    - Methodology for re-qualifying (a.k.a., de-rating) COTS for space are being developed
- **Lack of missions that can tolerate risk: if a lower performing non-MEMS part is available, but has more reliability data, the standard part is used.**

MEMS in space

- **Who is developing MEMS for Space?**
  - Mostly universities (with increasing NASA, ESA, DARPA, EU funding …)
  - Too small a market for the major MEMS foundries (Bosch, TI, etc)
  - Some internal R&D at major space companies like EADS Astrium, as well as at some national agencies (e.g., CNES) and JPL
  - Some small companies, e.g., NanoSpace (Sweden)
- **Who is flying MEMs for space?**
  - As more universities build cubesats and other nanosats, there are more opportunities for very high risk missions, as well as missions that can only work with MEMS.
- **Nanosats as MEMS test beds, for instance:**
  - Delft University Delfi 3C (2008)
  - PRISMA (June 15 2010)
  - OPAL
  - Proba-3 (2011)
  - SwissCube, flying since 9-2009 swisscube.epfl.ch

"Space Junk"

U.S. Strategic Command publishes a list of over 13'000 objects in orbit
http://adn.agi.com/SatelliteDatabase/SatelliteDatabase.kmz

Debris in Google Earth

http://www.esa.int/SPECIALS/ESOC/SEMN2VM5NDF_mg_1.html

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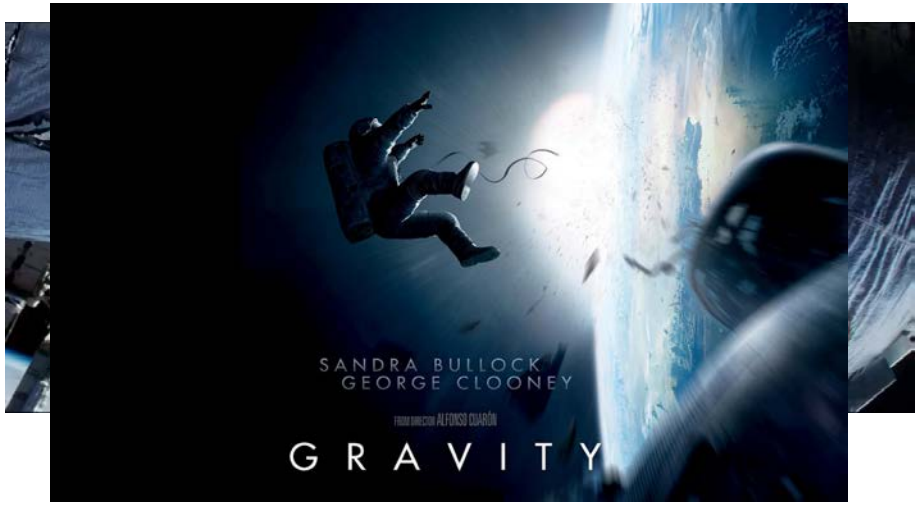
Are debris a real problem?



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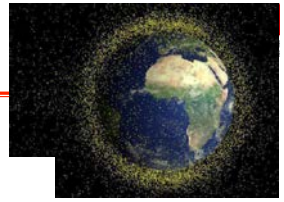
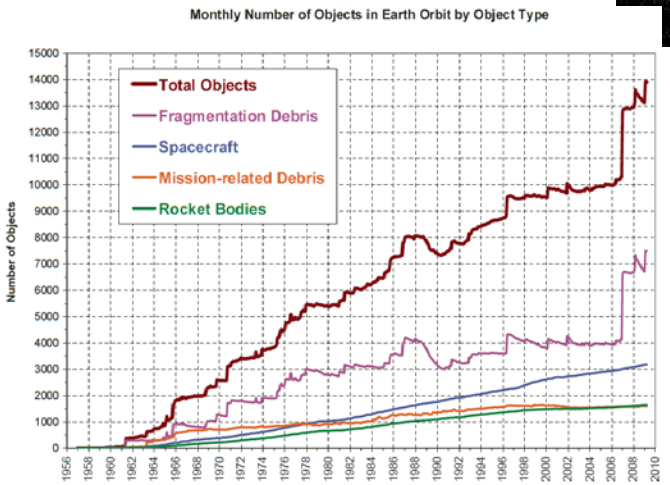
More and more debris





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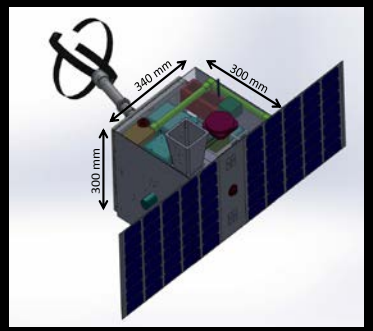
Towards a solution: actively removing debris!

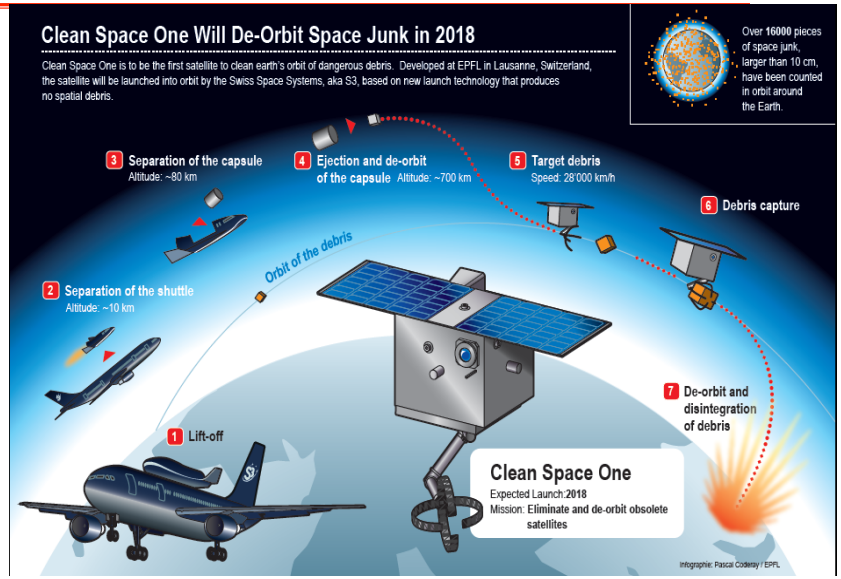
Mission CleanSpace One!

Microsatellite (30-40 kg) to grab and de-orbit debris



First target:
SwissCube, volume 1 liter, 750 km altitude, polar orbit

CleanSpace One **Mission Concept**



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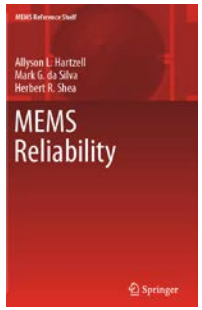
MEMS Reliability

Brief overview of reliability in the context of Space.

"MEMS Reliability"
by Hartzell, da Silva, Shea
part of the MEMS reference shelf series
Springer, 2011, ISBN 978-1-4419-6017-7

free download for EPFL staff at
http://link.springer.com/book/10.1007/978-1-4419-6018-4/page/1



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some possible failure modes of MEMS

- **Mechanical**
  - Contact: Friction, Wear, Stiction
  - Flexing: Fatigue, Work Hardening, Fracture
  - Creep, Plastic Flow
  - Thermal Coefficient Mismatch
  - Delamination, Residual Stress Compensation
  - Shock and vibration resistance
- **Electrical**
  - Corrosion, Anodic Oxidation
  - Galvanic corrosion in HF during release
  - Dielectric Charging, Drift
  - Shorts, Opens across dielectrics
  - Arcing, Modified Paschen Curve at small gaps
  - ESD

➢ **Design (*and Package*) for Reliability**

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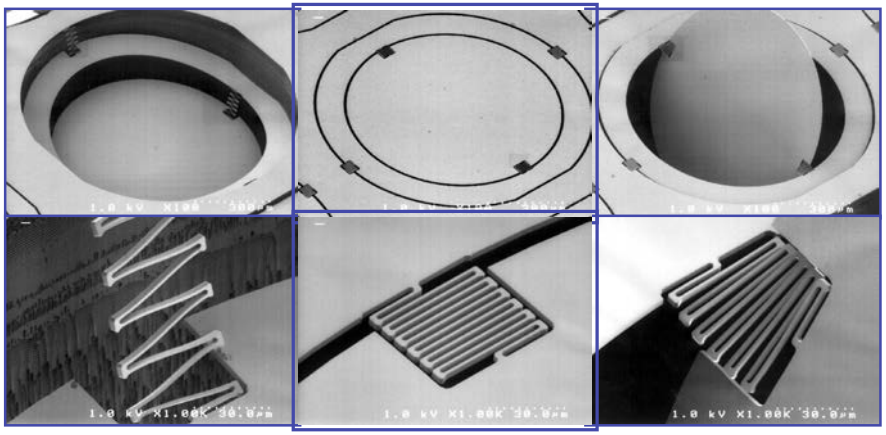
Flexing Silicon…

Single-crystal Si Structures (SOI)

Lucent Technologies
Bell Labs Innovations



unstressed springs

SEM images courtesy Lucent Technology

Silicon: amazing structural material
+
Conservative designs (<20% of yield strength)
} **Extremely reliable mechanically**

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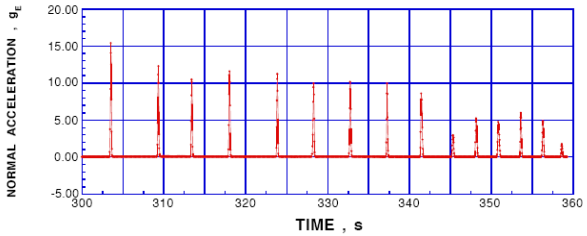
Space specific reliability issues

- **Vibration / Shock**
- **Radiation**
- **Temperature Range and Cycles**
- **Vacuum**
- **Oxygen Plasma**

Shock and vibration in space applications

- Static loads of a few G from launch are easy (trivial) to accommodate. (e.g., 2-5 G for Ariane 4, less for manned flights)
- Shocks of up to 1000G can readily be dealt with by spring design (avoid stress concentration, symmetrical designs…)
- Shocks of 10'000G from separation pyrotechnics require more careful design (of MEMS but also of attachment and package).
- Landing a rover : 20-100G (approx 30G for airbag landing on Mars)

F=ma but *m* is only a few µg



Shock

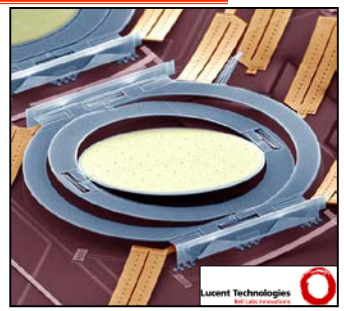
- **What can happen at high shock?**
  - Fracture
  - Stiction
  - Delamination
  - Shorts / mechanical blockage due moving particles
  - Package and die-attach can fail too (often more likely to fail than MEMS because of larger mass)

Solutions:
- Design to minimize stress
- Stopper to limit motion
- Anti-stiction coatings

Example: Shock resistance of Lucent Poly-Si micromirror

- Mirror:
  - 2.5 µm thick, 250 µm radius
  - Mass = 1 µg
- Beams:
  - t = 2.5 µm, w = 2.0 µm
  - L = 8 x 50 µm
- Polysilicon : $\sigma_{fracture}$ ~1 GPa

$$a_{fracture} = -\frac{2}{3}\sigma_{fracture}\frac{wt^2}{mL}$$



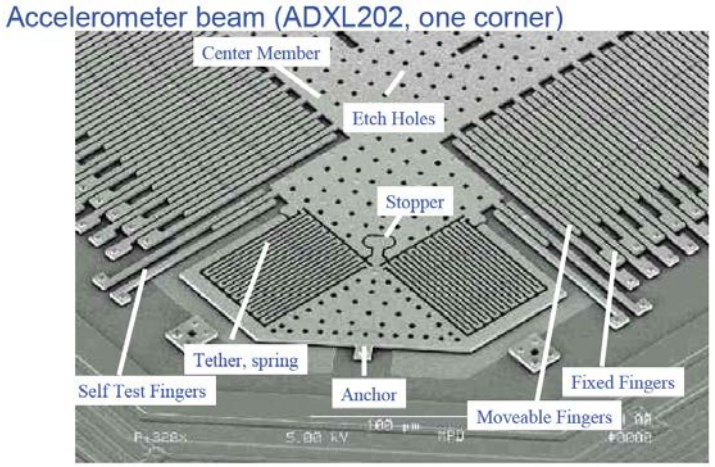
(for 4 spring suspension, pure piston motion, including a factor of two for dynamic loading, and assuming resonant modes of device are not excited by shock)

Maximum sustainable shock in piston mode computed to be 18'000G

Measured 3000 to 5000G for fracture: modeling is not too far off (Weibull distribution)

See also "MEMS Reliability in Shock Environments", by D. Tanner et al., Proceedings of 38th annual Reliability Physics Symposium (IRPS), 2000, p. 129

Mechanical Stoppers: limit motion

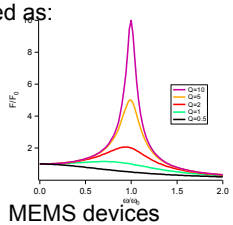


Robustness of MEMS to mechanical vibrations

• Requirements are launcher and mission dependent. Maximum for most space applications is 20g amplitude over the frequency range 5 Hz to 2000 Hz. For example, 7.3 G_{rms} for the Ariane 4 launcher, 1G from 5-100 Hz

• Key factors are coupling of the frequency ω of the applied vibration with the natural frequency ω_o of the MEMS structure and the quality factor Q of a given mechanical mode. The applied mechanical force F_0 is amplified as:

$$F = \frac{F_0}{\sqrt{\left((1-\frac{\omega^2}{\omega_0^2}\right)^2 + \frac{1}{Q^2}\frac{\omega^2}{\omega_0^2}}}$$



•To minimize the force amplification due to the coupling effect, MEMS devices should be designed to have ω_o > 2000 Hz or Q<3

•Proper device design should keep the max acceleration due to applied vibration well under 100G eliminating the possibility of fracture of the MEMS parts

Well designed silicon MEMS devices can be extremely robust to mechanical vibrations and shock (very stiff and light)

Radiation on MEMS

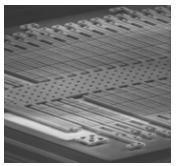
- Radiation damage:
  - Atomic displacement : displacement damage
  - Ionization: electron-hole pair, can lead to trapped charge
- Even at the high end of space doses, mechanical properties are mostly unchanged (Young's modulus, yield strength).
  - Silicon as a structural material is intrinsically radiation hard (as compared to electronics)
- MEMS themselves typically have no p-n junctions or semiconducting regions where doping and carrier concentration plays an important role (except for piezo-resistors)
- However the electronic properties, especially of dielectrics (insulator) can be modified.
- **Data on MEMS under radiation clearly show charge build-up in dielectrics as main effect**
- (Control electronics needs to be rad-hard however)

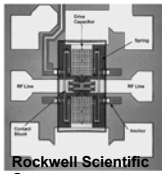
Radiation and charge injection

- **Limited data, mostly on accelerometers and RF switches (commercially available)**
- **Data on unpackaged (unshielded) devices:**
  - Sandia Micro-engines: 10 MRads (no dielectrics involved)
  - Unpackaged accelerometers (Analog Devices ADXL50): change observed at 20 to 100 kRad
  - RF switches: 10 kRad to 300 kRad
- **Failure (degradation) always due to charge build up in dielectric used as an isolator.**

➢ Must locally remove dielectric, or provide a charge dissipation path

Sandia National Labs


Analog Devices


Rockwell Scientific Company

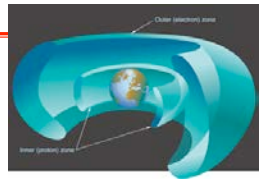
Review paper: "Radiation sensitivity of microelectromechanical system devices", H. Shea, *Journal of Micro/Nanolithography, MEMS, and MOEMS, vol. 8, num. 3, 2009, p. 031303, 2009*

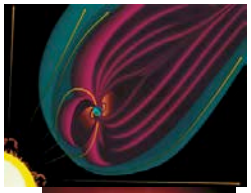
Radiation near Earth

The main radiation encountered near Earth:

1. **Trapped radiation**: energetic electrons and protons magnetically trapped around the earth (2 Van Allen belts). They consist of electrons of energy up to a few MeV, and protons of up to several hundred MeV.
2. **Solar Energetic particles**: mostly highly energetic protons, up to 300 MeV. The intensity varies greatly in time, especially the 11 year solar cycle. UV and X-ray burst are also produced, as well as solar cosmic rays.
3. **Galactic cosmic-rays**: continuous low flux of highly energetic (1 MeV to 1 GeV) particles, mostly protons, alpha particles, but also include heavy ions.
4. **Secondary radiation**: radiation generated when the above radiation interacts with materials in the spacecraft, notably with shielding.

Complex, time dependent

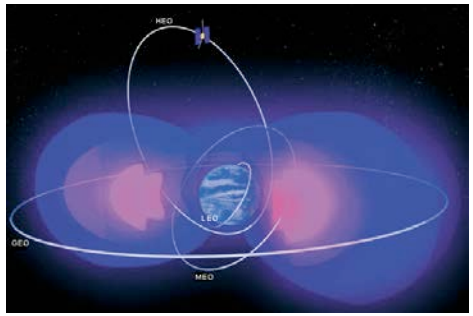




Images from http://www.aero.org/publications/crosslink/summer2003/02.html

Dose depends strongly on orbit !

- Low Earth Orbit (LEO): well shielded, below radiation belts
- Geostationary (GEO): much more exposed, but above radiation belts
- Highly Elliptical Orbit (HEO): twice a day through the radiation belts
- GPS orbit: in radiation belts



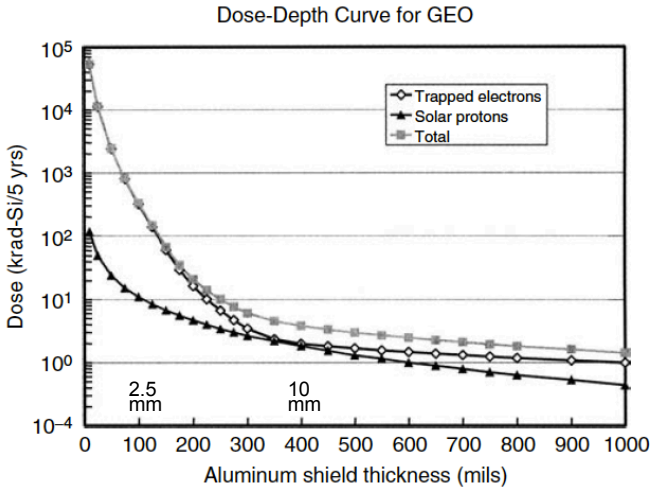
(Illustration by B. Jones, P. Fuqua, J. Barrie, The Aerospace Corporation.)

Units

- The effect of the many different types of radiation on components can be summarized by the quantity of energy deposited by the radiation.
- The SI unit is the Gray (1 J/kg), but the unit rad (1 rad = 10^{-2} Gray = 100 erg/gram) is still in common use.
- Total Ionizing radiation Dose (TID), defined as the Ionization energy per unit mass, leads to an accumulation of electrically active defects.

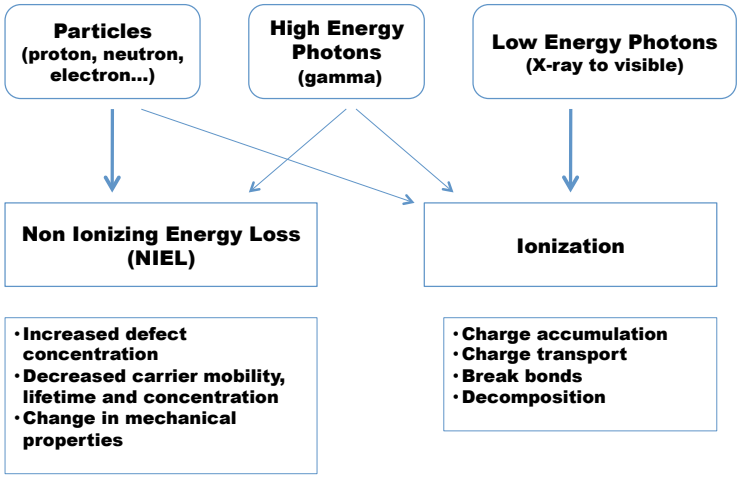
Trajectory , shielding	Predominant particles	Dose deposited per year
LEO , outside S/C	Trapped electrons	> 100 krad
LEO, 4 mm Al equivalent	Trapped protons	1 krad
GEO , outside S/C	Trapped electrons	> 10'000 krad
GEO, 4 mm Al equivalent	Bremsstrahlung + solar protons	10 krad

Shielding



From J. Barth, *Modelling Space Radiation Environments*, IEEE, 1997

Radiation-induced degradation



https://escies.org/ReadArticle?docId=263

So what happens for MEMS?

- **MEMS actuation or sensing principles**
  - Capacitive (electrostatic)
  - Piezoresistive / piezoelectric
  - ElectroMagnetic
  - ElectroThermal
- **MEMS materials**
  - Silicon
  - Metals
  - Polymers
  - Glass

Degradation Effects - Mechanical

Metals

no mechanical changes at space doses

Semiconductors

no mechanical changes at space doses

Insulators

no mechanical changes at space doses

Polymers

Important changes in stiffness, brittleness

Degradation Effects - Electrical

Metals

none

Semiconductors

Serious problem

- Displacement damage leads to a change change in minority carrier lifetime and concentration and mobility,
- important effect on p-n junctions (rectifiers and bipolar transistors, as well as solar cells)
- Can influence Si-based piezo-resistors

Degradation Effects - Electrical

Most of the energy lost from radiation interacting with an absorber is ultimately converted to electron-hole pairs (the energy required is only 18 eV for SiO_2)

Insulators

- For dielectrics, ionizing radiation leads to both:
  - direct charge injection from ionizing radiation, and
  - the creation of deeper traps and possibly more defects, thus making the dielectric even more susceptible to charging from non-radiation related sources.
  - Electrons and holes have very different mobilities. Holes can become trapped in insulators (SiO_x, SiN_x), leading to serious degradation of MOS and MEMS devices
- The influence of the trapped charge depends on the actuation scheme (electrostatic is much more sensitive), and on the geometry, such as the presence or absence of conductive shields to screen the trapped charge.

ADI Poly-Si accelerometer ADXL50

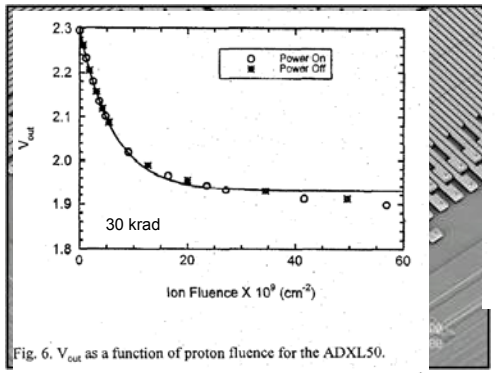


Fig. 6. V_{out} as a function of proton fluence for the ADXL50.

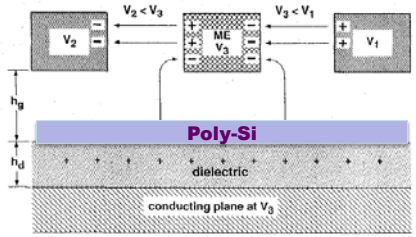


Fig.3: Side view of one sensor cell illustrating the horizontal force. For a positively charged dielectric, the resulting field (nominal plus fringing) and net charge (nominal plus induced) are both stronger on the right side of the ME.

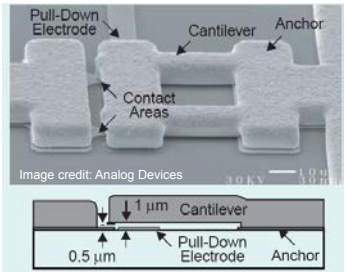
Adding a poly-Si layer of the dielectric (ADXL04) eliminated the shift in V_{out} due to radiation

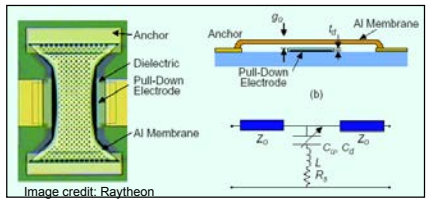
Knudson, et al "The effects of radiation on MEMS accelerometers." IEEE Transactions on Nuclear Science 43, no. 6 (1996)

Edmonds, et al "Radiation Response of a MEMS Accelerometer : An Electrostatic Force." *IEEE Transactions on Nuclear Science* 45, no. 6 (1998): 2779.

MEMS RF switch

- **RF MEMS switches offer:**
  - Lower insertion loss (0.1dB @ 40GHz)
  - High isolation (>40 dB)
  - Large frequency range (up to 120 GHz)
  - Extremely high linearity (important!)
  - Low power consumption
- Two main designs: capacitive and contact (ohmic)
- High performance enables new architectures and simpler circuit design
- Phased array for beam steering is a prime application, as well a smart antennas and routing.





Figures reprinted from "RF MEMS switches and switch circuits" by G.M. *Rebeiz and J.B. Muldavin*, in IEEE Microwave Magazine, Volume: 2 Issue: 4 , 2001 pp. 59 -71

Ohmic RF MEMS switch from Rockwell Scientific

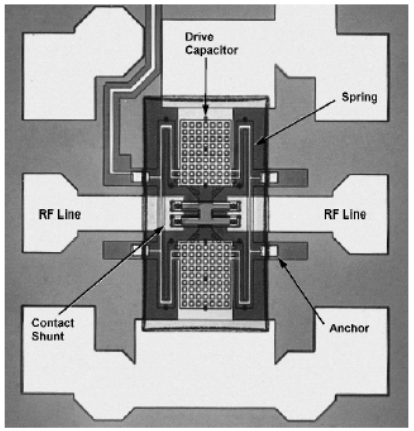


Fig. 1. Top view of the RSC MEMS RF switch. The center structure is suspended by the four metal springs. Application of voltage to the drive capacitor actuates the switch.

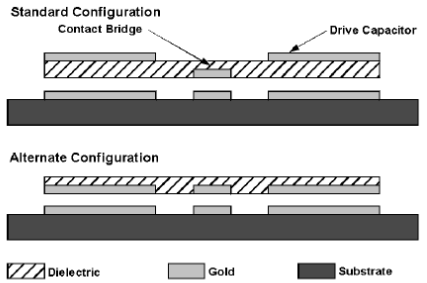


Fig. 2. Cross section of standard and alternate configurations of the RSC RF MEMS switch.

McClure, S.S., et al, "Radiation effects in micro-electromechanical systems (MEMS): RF relays." *IEEE Transactions on Nuclear Science* 49, no. 6 (December 2002): 3197-3202.

Ohmic RF MEMS switch

Gamma irradiation

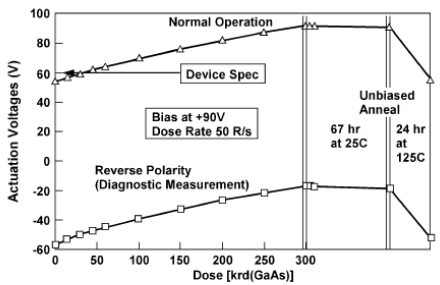


Fig. 3. Actuation voltage versus dose for the standard configuration biased positively during irradiation.

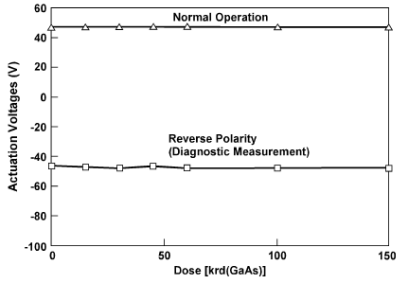
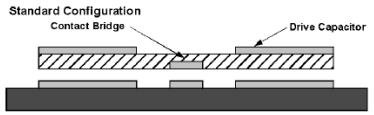
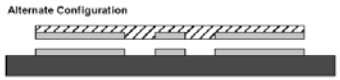


Fig. 5. Actuation voltage versus dose for alternate configuration biased positively during irradiation. No measurable change in actuation voltage was observed.

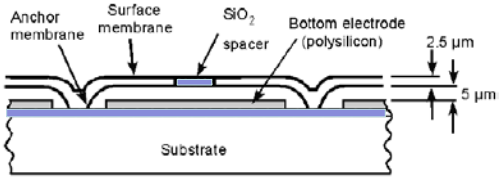




McClure, S.S., et al, "Radiation effects in micro-electromechanical systems (MEMS): RF relays." *IEEE Transactions on Nuclear Science* 49, no. 6 (December 2002): 3197-3202.

Rad-hard electrostatic MEMS

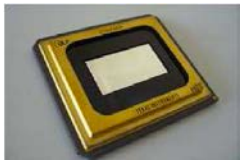
- Boston Micromachines (BMM) mirror array (electrostatic parallel plate): no failures up to 3 Mrad



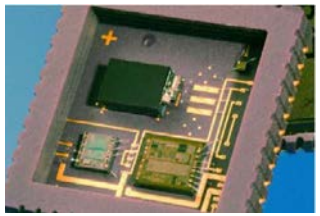
- Sandia National Labs microengines (electrostatic combdrive), up to 100 Mrad (x-ray) to 5 Grad (proton)
  - Poly-Si layer, effectively shields trapped charge in SiN or SiO layer
  - Strong dependence on whether electrodes are grounded (=good) or biased (=bad) during irradiation.

Control Electronics

If Control electronics are monolithic or in same package, can be hard to separate MEMS failure from CMOS failure



- TI DMD mirrors tested by Zamkotsian et al, degradation around 15 krad (gamma)
- Motorola XMMAS40G, 4k rad (gamma)
- Colibrys accelerometer MS8002, 4-8 krad (proton, gamma)
- VTI SCA 600, 50 krad



Need radiation tolerant electronics!

Conclusions on radiation on MEMS

- Electrothermal and electromagnetic actuation principles are intrinsically more radiation tolerant than electrostatic operation
- There is much improved understanding of how to mitigate dielectric charging (e.g. for RF switches), which is directly applicable to making electrostatic MEMS more radiation hard
- Control electronics need to be rad hard too!
- In practice, control electronics is a bigger problem than the MEMS device
  - Ironic, as it is known how to make radiation tolerant
  - But MEMS for mass market are tightly integrated with their control /sensing circuitry
- Radiation tolerance will not be the major obstacle to MEMS in space

Example: RF MEMS

© 2014 EPFL

AFM on Mars within the Phoenix mission

Partners:

Institute of Microtechnology, Neuchâtel
Imperial College, London
Institute of Physics, Univ. of Basel
Jet Propulsion Laboratory
Nanosurf AG, Liestal

Landed May 2008!!!

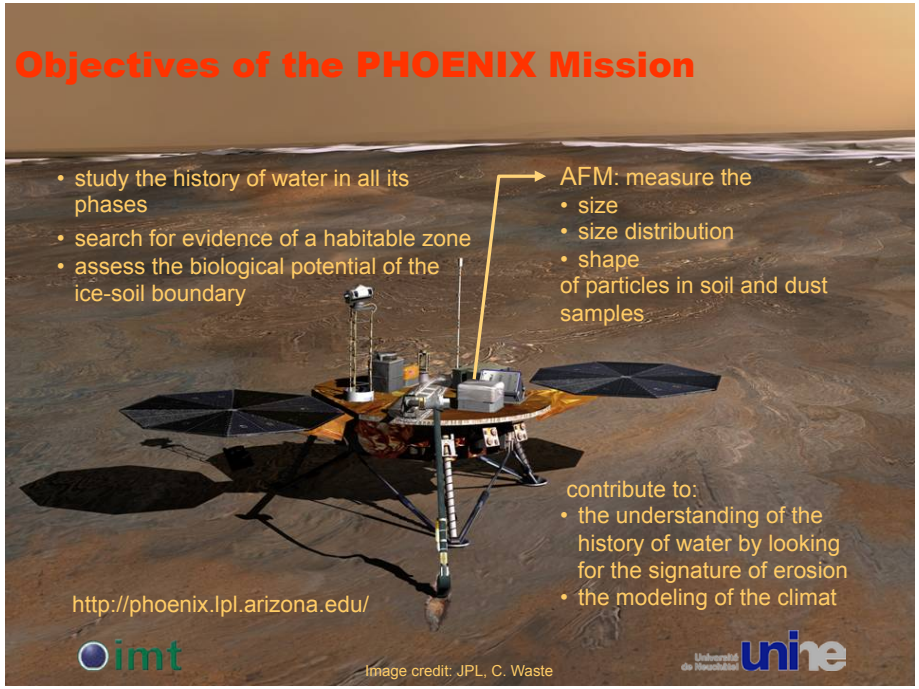
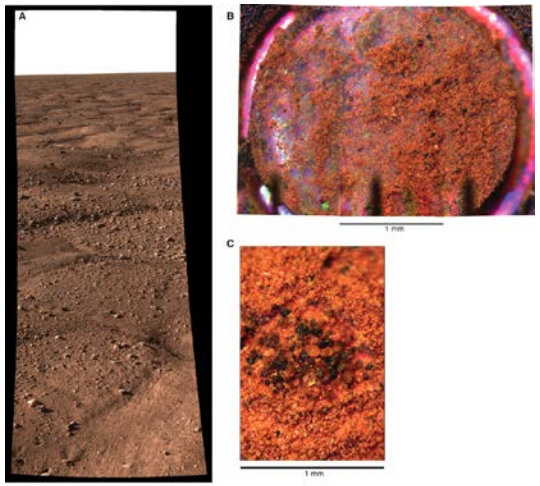


Fig. 1 (A) Sol 0 image of the patterned ground shaped by subsurface ice

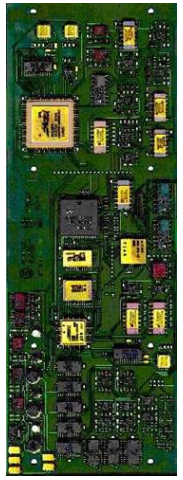


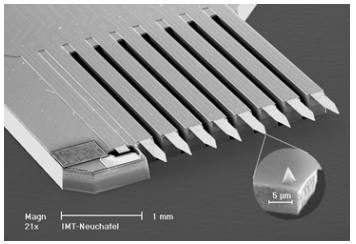
P. H. Smith et al., Science 325, 58 -61 (2009)

Components of the Mars AFM

electro-magnetic
x-y-z scanner

single board
controler, based
on digital a
feedback loop

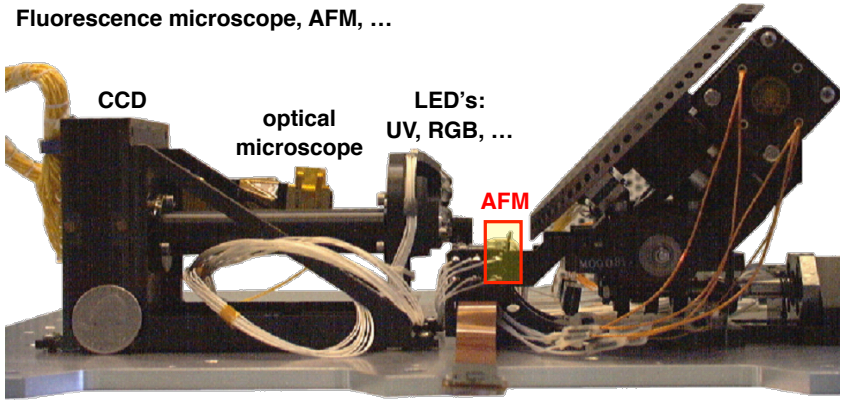




AFM sensor chip
with 8 levers for
redundancy

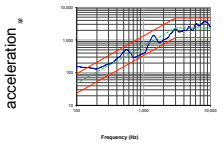
MECA microscopy station

- Mars Environmental Compatibility Assessment (MECA)
- Phoenix Mission 2008
- Analysis of dust and soil particles: shape, size, hardness, …
- Fluorescence microscope, AFM, …

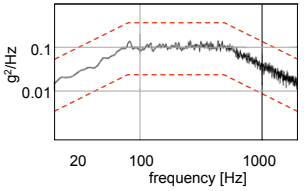


Tests: shock, vibration, Mars-conditions

up to 2370 g



spectrum from
20 to 2000 Hz at
12 g rms

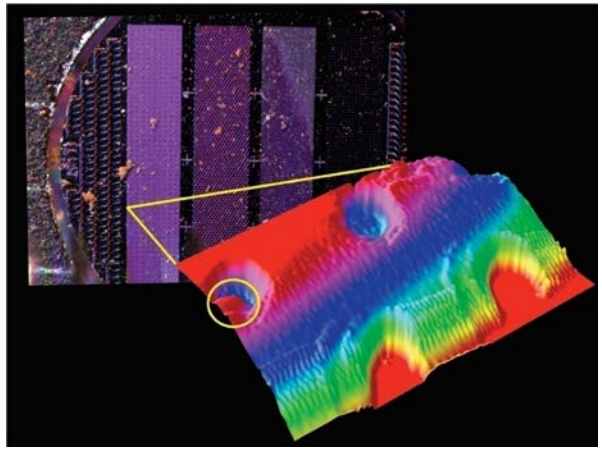


gas (N_2, CO_2)

pressure (~1mbar)

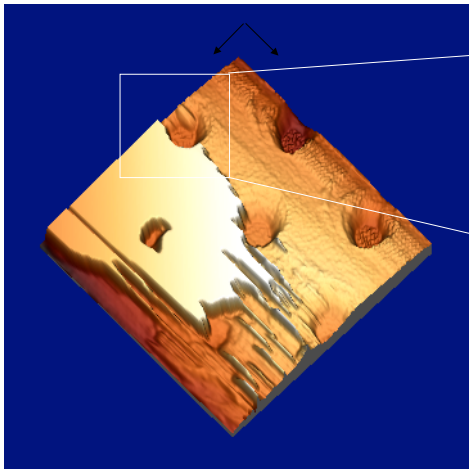
Cooling (-50°C)

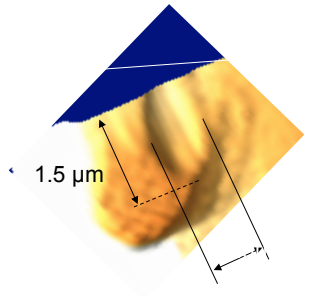
AFM data from Mars!!



First extra-terrestrial AFM image !
Only possible with MEMS technology

L'AFM fonctionne sur Mars et a renvoyé des images!!
Scan de particule de poussière marsienne



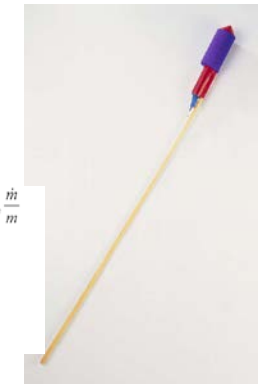


Example: Propulsion

Micropropulsion

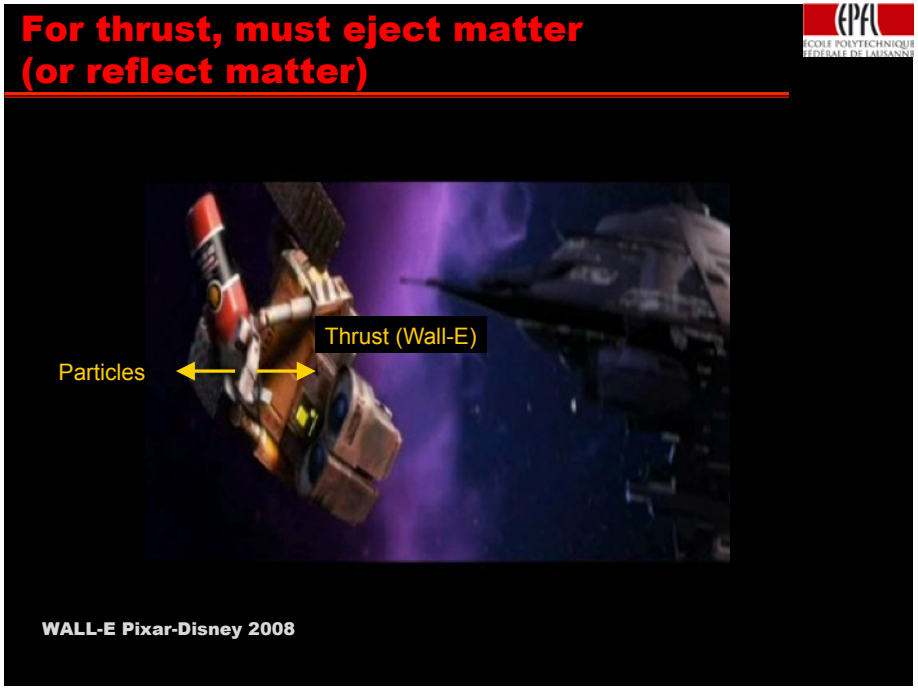
action = reaction

For Thrust, need to eject:
- gas (hot or cold)
- liquid
- ions



- The acceleration provided to the spacecraft is then: $\frac{dv}{dt} = \frac{F_{th}}{m} \Rightarrow \frac{dv}{dt} = v_e \frac{\dot{m}}{m}$
- Integrating over the duration of the burn: $\Delta v = v_e \ln(\frac{m_i}{m_f})$
- Rocket Equation or Tsiolkowski Equation: $\Delta v = g_o Isp \ln(\frac{m_i}{m_f})$

For thrust, must eject matter (or reflect matter)



MEMS micro-propulsion

- **Propulsion is an action that creates movement**
  - Rocket propulsion: movement of a satellite created by the expulsion of thermodynamic, electro-magnetic or otherwise accelerated gas
- **A propulsion systems consist of a storage, a feeding system, one or more thrusters and sensors to monitor it**
- **Micro propulsion today has two definitions !**
  - Very low (mN or smaller) and often accurate and controllable thrusts coming from devices that have a large mass and need a lot of power
    - For example FEEP propulsion, 7 kg and 150 W for 1 mN
  - Small or miniaturised propulsion systems for small satellites often using miniaturised (MST) technologies and mostly having small thrusts
- **We will focus here only on small or miniaturised propulsion systems based on microsystems technology**
  - Thrust µN to 1 N, Mass < 1 kg

Propulsion for small satellites: what for?

- **Small satellites in space can experience:**
  - Drag from atmosphere
  - Gravity gradient
  - Photon pressure
  - Magnetic torques
- **Small satellites are getting more and more capable**
  - For Attitude control, passive control is not good anymore
  - For Orbit control, just being in space is not enough
    - Orbital manoeuvres, orbit change after launch
    - Maintaining the right orbit for your mission (station keeping)
    - De-orbit after your mission
  - Formation flying is very important in future missions and mission concepts
- **Propulsion is the only way available to perform formation flying, the most flexible option for orbit control and an option for attitude control**
- **micro propulsion is vital for the future of small satellites**

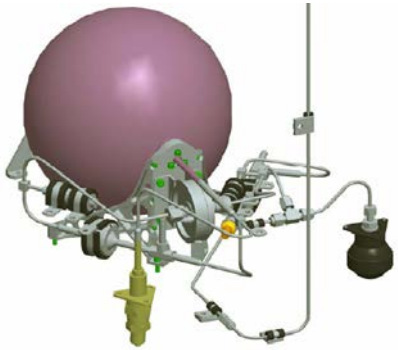
Propulsion systems

- **Electrical propulsion**
  - Pulse plasma thruster
  - Vacuum arc thruster
  - FEEP
  - Laser ablation thruster
  - Micro Ion-thruster
  - Micro-Resistojet
- **Chemical propulsion**
  - Cold gas thruster
  - Solid propellant thruster
  - Liquid propellant thruster

Cold gas thrusters

- **From NanoSpace, Sweden**

www.nanospace.se

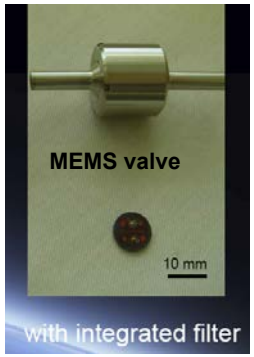


MEMS Components
- Filter
- Isolation valve
- Pressure sensors
- Relief Valve
- Proportional valves
- Nozzles, channels, chambers, heaters, vias…

Experiments to verify thrust from 10 µN to 1 mN

Cold gas thrusters

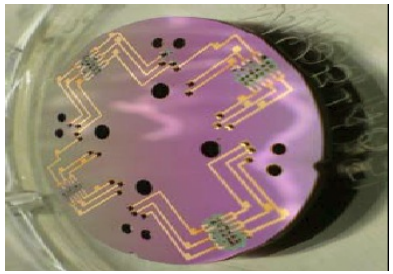
- **From NanoSpace**



MEMS in pod assembly
- Four microthrusters per pod
- Filters
- Channels and vias
- Stagnation chamber
- Nozzles
- Heaters for hot gas mode

Cold gas thrusters

- **From NanoSpace**



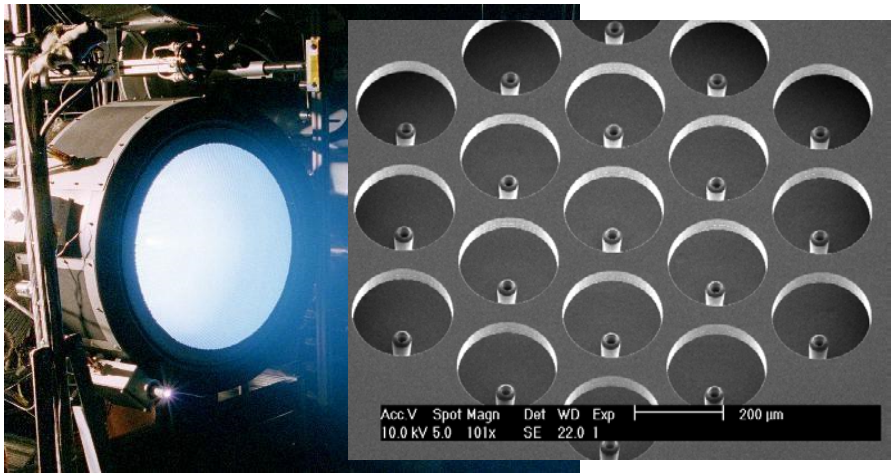
- **Thrust range: 10 µN to 1 mN**
- **Specific Impulse: 50 - 100 sec (higher with heated gas)**
- **Power consumption: < 1W (per thruster)**
- **Mass: < 110 g (thruster pod)**
- **Dimensions: 43.5 mm (diameter) 51 mm (height)**

Flown in Sept 2010 on Mango/Tango

http://www.enjoyspace.com/en/news/mango-tango-s-space-dance

Micromachined Ion source for electric propulsion

Ion thruster prdocuce very low thrust, but high ISP (efficient use of propellant)

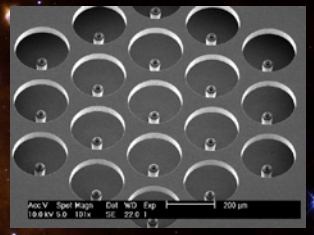


NASA NSTAR

EPFL-LMTS

Micromachined Electrospray Thrusters for Spacecraft Propulsion:

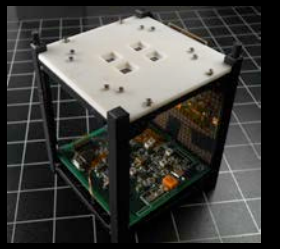
lightweight low-thrust (μN-mN) propulsion system for spacecraft orbit and attitude control



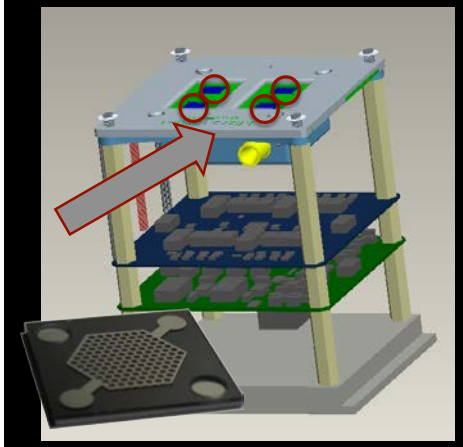
Objectives of MicroThrust

www.microthrust.eu

- We address the lack of efficient low-mass propulsion for small (1-100 kg) spacecraft
- We will enable: much lower cost and missions using nanosatellites for science missions in LEO, to the moon, asteroids and even other planets
- How? By developing a complete miniaturized electric propulsion system:
  - ISP: 3000s (for 5 km/s ΔV)
  - Modular
  - Sized for cubesats volume & power
  - Simple, reliable, scalable



MicroThrust: Developing a thruster system for small spacecraft



Complete module (concept):

- Wet mass: < 300g / kg of launch (30%)
- Power: <5 W @ 3.5 kV
- Dimensions: < 10cm x 10cm x 10cm

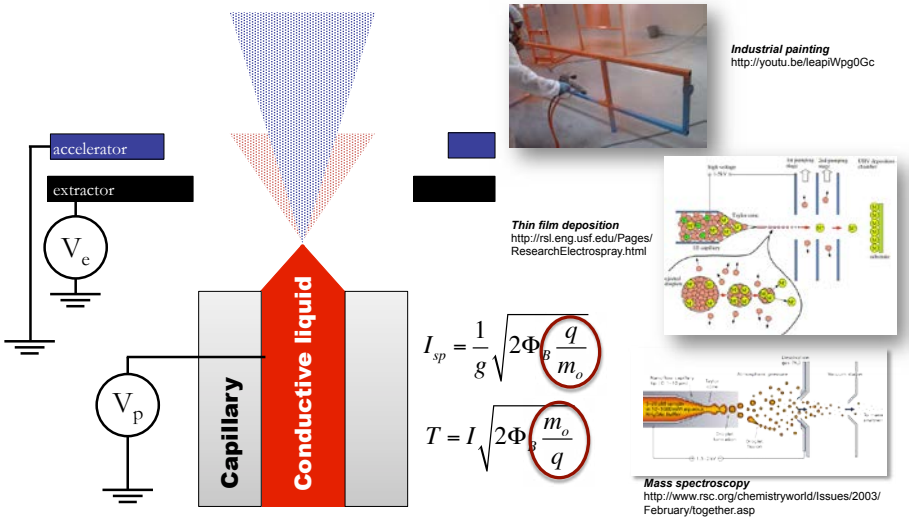
- Isp: > 3000s
- Thrust: 20 μN/W
- **ΔV: 5 km/s**

Partners:

- EPFL (Switzerland)
- Queen Mary University of London (UK)
- Nanospace (Sweden)
- TNO & SystematIC (Netherlands)

http://www.microthrust.eu

Basic operation of electrosprays



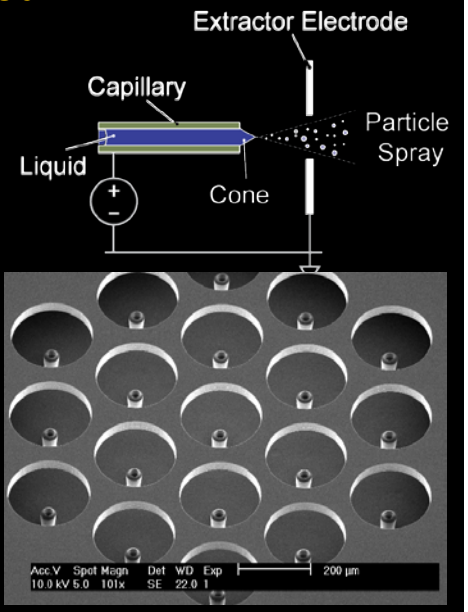
Microfabricated solution

- **Arrays** of thrusters with individual extraction electrodes enable:
  - Large thrust range (µN to mN)
  - Redundancy
  - Lower operation voltage
  - High ISP (by operating in ion regime)
  - Simple operation (no active pumping)

© 2014 EPFL

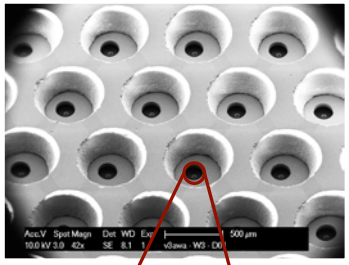
MicroThrust is based on electrospray

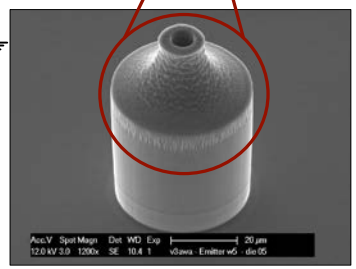
- By using an ionic liquid, we can choose to emit ion (high ISP; lower thrust) or droplets (lower ISP, higher thrust)
- Using MEMS array to get both high thrust and high ISP

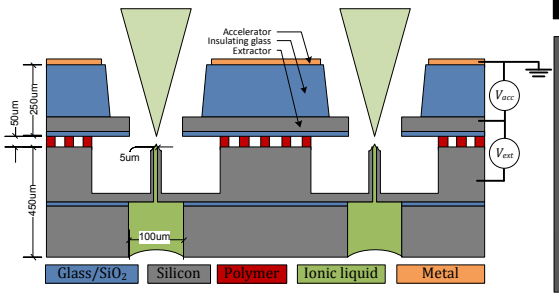


Our design of electrospray emitters

- Out of plane hollow needle emitter arrays
- Capillary and electrode levels are microfabricated separately
- Batch assembly with wafer bonding







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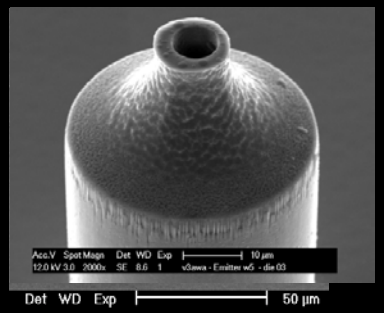
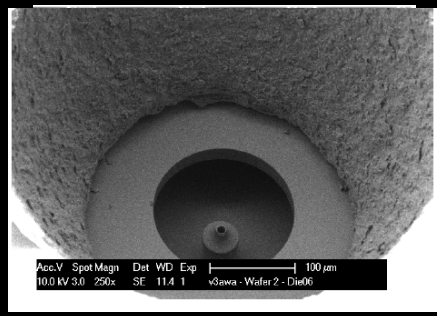
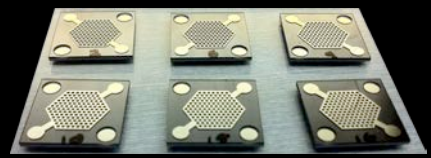
Silicon Capillaries

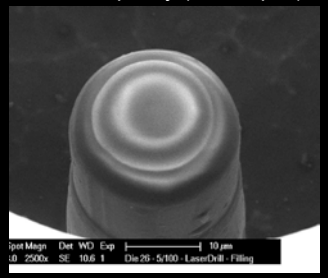




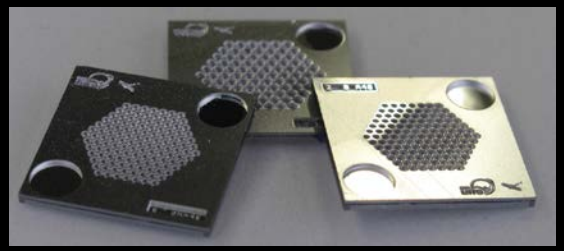


MEMS µThruster

Filled capillary (ionic liquid)



Assembled thruster



MicroThrust electrospray thruster to lunar orbit

MEMS Electric Propulsion system allows for high performance

- We have fabricated a miniaturized colloid thruster chip, using ionic liquids as propellant
  - Emits ions at up 40 km/s
  - Very efficient use of propellant mass
  - Highly integrated wafer-scale process, 127 emitters/chip
- Thruster is batch fabricated from silicon wafers, to provide sufficient thrust (up to 300 µN) for a wide variety of missions for satellites of mass 1-100 kg
- Working with European consortium MicroThrust (FP7 Space) on testing a full thruster system.

Getting MEMS into space, a practical example

Need to demonstrate operation in space!

How to fly these technologies??

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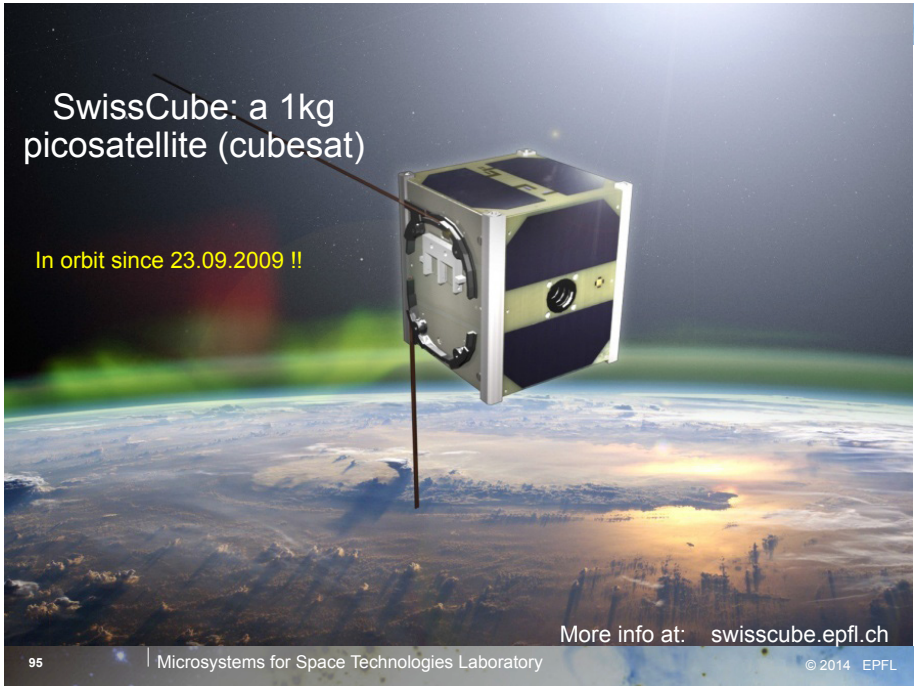
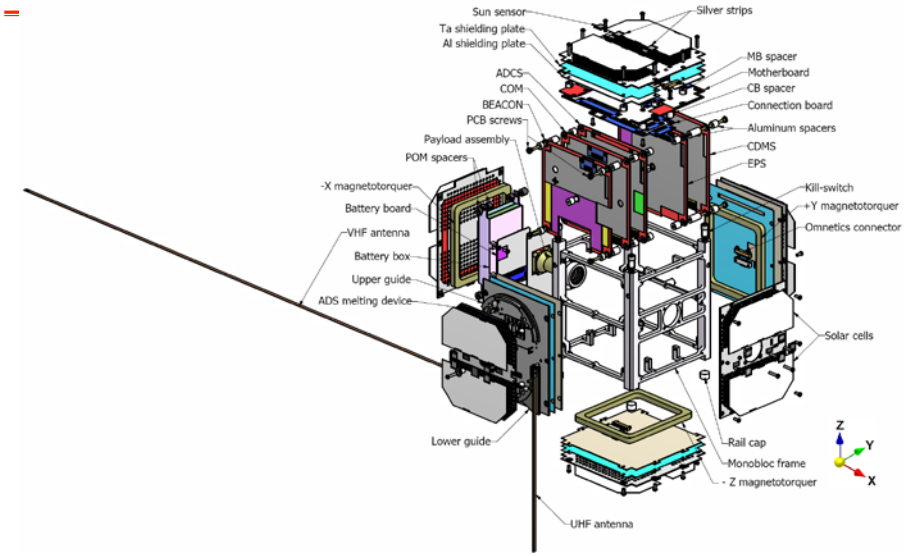
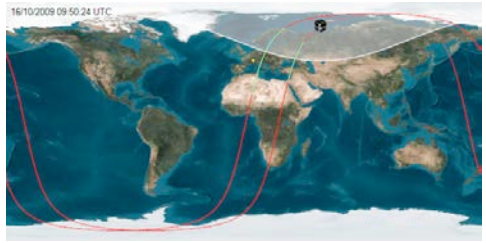


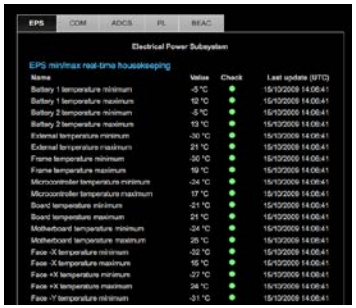
Exploded View of the Flight System



Swisscube in orbit!

- Satellite launched Sept 23th 2009
- Orbit: sun-synchronous 720 km altitude





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Conclusions

Reliability is a major issue for space applications:

• Physical sensors (accelerometer, gyroscopes) that have been on the market for a while have proven to be robust and the technology is available for space applications

• MOEMS and RF MEMS are gaining in maturity on earth and are slowly getting into space applications

• Propulsion systems in terms of reliability and reproducibility still need further development but can provide key abilities to nanosats for orbit changes and formation flying

• Validation and qualification of the components are critical steps in the next coming years to see more MEMS in space

• Micro & nano satellites initiatives are the key platform to test a broad range of MEMS components in order to validate them for larger space systems

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Outlook

Once a wide variety of types of MEMS are validated:

- More than just satellites:
  - Rovers, planetary exploration, probes, constellations…
- Lower cost and higher performance in large satellites
  - Redundancy of parts in satellites
  - Lower Launch cost by reduction of weight
- New missions and spacecraft architectures enabled by MEMS:
  - Faster development thanks to use of MEMS component libraries
  - Constellation of small satellites in space (mass production)
  - Scientific experiments based on micro-instrumentation

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Questions ?

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