MEMS for Space
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“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.

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

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
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

<table>
<thead>
<tr>
<th>Group name</th>
<th>Wet Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large satellite</td>
<td>&gt;1000kg</td>
</tr>
<tr>
<td>Medium sized</td>
<td>500-1000kg</td>
</tr>
<tr>
<td>Mini satellite</td>
<td>100-500kg</td>
</tr>
<tr>
<td>Micro satellite</td>
<td>10-100kg</td>
</tr>
<tr>
<td>Nano satellite</td>
<td>1-10kg</td>
</tr>
<tr>
<td>Pico satellite</td>
<td>0.1-1kg</td>
</tr>
<tr>
<td>Femto satellite</td>
<td>&lt;1kg</td>
</tr>
</tbody>
</table>

Cubesat!

About 40 have been launched, 80 under construction

Standard format: 1 kg, 1 liter (or 3 kg 3 liters)

Image credit: NASA

MEPSI deployed from space shuttle
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.

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/SEM2VM5NDF_mg_1.html

Are debris a real problem?

More and more debris

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
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

free download for EPFL staff at

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

Flexing Silicon...
Single-crystal Si Structures (SOI)
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 1000 G can readily be dealt with by spring design (avoid stress concentration, symmetrical designs…)
- Shocks of 10,000 G from separation pyrotechnics require more careful design (of MEMS but also of attachment and package).
- Landing a rover: 20-100 G (approx 30 G for airbag landing on Mars)

\[ F = ma \] but \( m \) is only a few \( \mu \)g

Example: Shock resistance of Lucent Poly-Si micromirror

- Mirror:
  - 2.5 \( \mu \)m thick, 250 \( \mu \)m radius
  - Mass = 1 \( \mu \)g
- Beams:
  - \( t = 2.5 \, \mu \)m, \( w = 2.0 \, \mu \)m
  - \( L = 8 \times 50 \, \mu \)m
- Polysilicon: \( \sigma_{\text{fracture}} \approx 1 \) GPa

\[ a_{\text{fracture}} = \frac{2}{3} \frac{\sigma_{\text{fracture}}}{mL} \frac{wt^2}{mL} \]

Maximum sustainable shock in piston mode computed to be 18,000 G
Measured 3000 to 5000 G 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

- 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_{max} for the Ariane 4 launcher, 1G from 5-100 Hz
- Key factors are coupling of the frequency $\omega$ of the applied vibration with the natural frequency $\omega_0$ of the MEMS structure and the quality factor Q of a given mechanical mode. The applied mechanical force $F_0$ is amplified as:

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

- To minimize the force amplification due to the coupling effect, MEMS devices should be designed to have $\omega_0 > 2000$ 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)
  - Unpacked 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

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

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

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.

<table>
<thead>
<tr>
<th>Trajectory, shielding</th>
<th>Predominant particles</th>
<th>Dose deposited per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO, outside S/C</td>
<td>Trapped electrons</td>
<td>&gt; 100 krad</td>
</tr>
<tr>
<td>LEO, 4 mm Al equivalent</td>
<td>Trapped protons</td>
<td>1 krad</td>
</tr>
<tr>
<td>GEO, outside S/C</td>
<td>Trapped electrons</td>
<td>&gt; 10'000 krad</td>
</tr>
<tr>
<td>GEO, 4 mm Al equivalent</td>
<td>Br第三 thuật + solar protons</td>
<td>10 krad</td>
</tr>
</tbody>
</table>

Shielding

From J. Barth, Modelling Space Radiation Environments, IEEE, 1997
Radiation-induced degradation

Particles (proton, neutron, electron...)
High Energy Photons (gamma)
Low Energy Photons (X-ray to visible)

Non Ionizing Energy Loss (NIEL)
Ionization

- Increased defect concentration
- Decreased carrier mobility, lifetime and concentration
- Change in mechanical properties

- Charge accumulation
- Charge transport
- Break bonds
- Decomposition

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 SiO₂).

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 (SiO₂, SiNx), 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.

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.

ADI Poly-Si accelerometer ADXL50

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


Ohmic RF MEMS switch from Rockwell Scientific


Ohmic RF MEMS switch


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!
  - 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

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!!!

Objectives of the PHOENIX Mission

- study the history of water in all its phases
- search for evidence of a habitable zone
- assess the biological potential of the ice-soil boundary

contribute to:
- the understanding of the history of water by looking for the signature of erosion
- the modeling of the climat

AFM: measure the
- size
- size distribution
- shape of particles in soil and dust samples

http://phoenix.lpl.arizona.edu/

Image credit: JPL, C. Waste
Fig. 1 (A) Sol 0 image of the patterned ground shaped by subsurface ice


Components of the Mars AFM

- electro-magnetic x-y-z scanner
- single board controller, 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

- Sample wheel
- CCD
- Optical microscope
- LED’s: UV, RGB, ...
- AFM
- spectrum from 20 to 2000 Hz at 12 g rms
- up to 2370 g
- gas (N₂, CO₂)
- 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

Micropropulsion

Example: Propulsion

action = reaction

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

Particles

Thrust (Wall-E)

WALL-E Pixar-Disney 2008

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

Micromachined Ion source for electric propulsion

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

Flown in Sept 2010 on Mango/Tango


HIM 2014 © 2014 EPFL

HIM 2014 © 2014 EPFL

HIM 2014 © 2014 EPFL

HIM 2014 © 2014 EPFL
Micromachined Electrospray Thrusters for Spacecraft Propulsion: lightweight low-thrust (μN-mN) propulsion system for spacecraft orbit and attitude control.

**Objectives of MicroThrust**

- 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)

**Basic operation of electrosprays**

\[ I_{sp} = \frac{1}{g} \sqrt{\frac{2q}{m}} \]

\[ T = I \sqrt{2q \frac{m}{\eta}} \]

**Thin film deposition**

http://www.rsc.org/chemistryworld/Issues/2003/February/together.asp

**Industrial painting**

http://youtu.be/leapiWpg0Gc

**Mass spectroscopy**

http://www.rsc.org/chemistryworld/Issues/2003/February/together.asp
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)

Our design of electrospray emitters

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

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

\[ I_{sp} = \frac{1}{\Phi B q} \]
\[ T = I^{2} \Phi B q \]

MEMS µThruster

Silicon Capillaries
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.
SwissCube: a 1 kg picosatellite (cubesat)

In orbit since 23.09.2009!!

More info at: swisscube.epfl.ch

Exploded View of the Flight System
Swisscube in orbit!

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

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

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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- Urs Staufer (now TU Delft) and Seb Gautsch (EPFL Samlab)
- Pelle Rangsten (NanoSpace)
Questions?

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