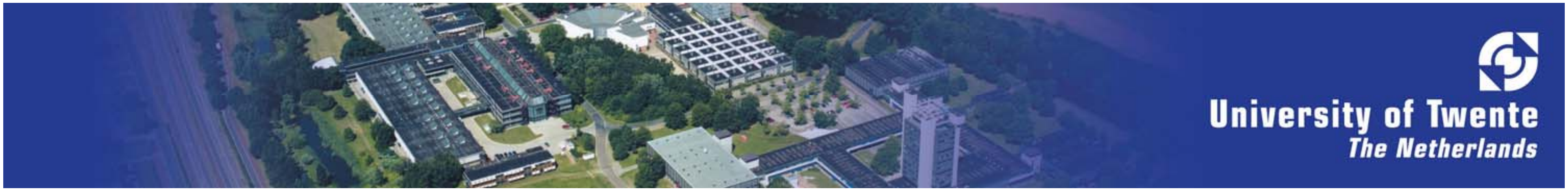
University of
Twente

MEMS based gravity gradiometer for Space Application

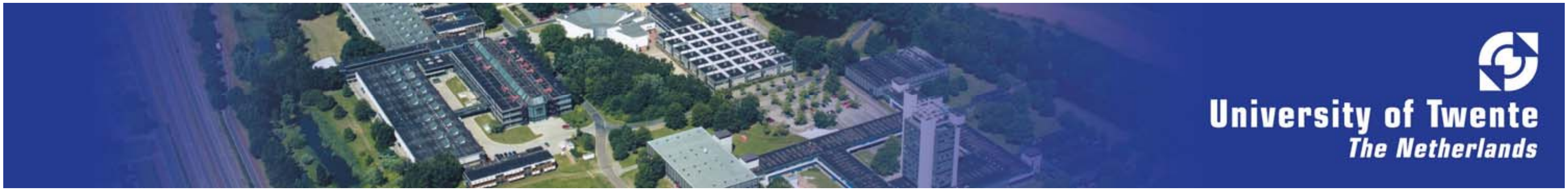
Twente: R. Cuperus, J. Flokstra, R.J. Wiegerink
TU Delft: P. Visser
SRON: A. Selig, M. Smit, J. Bouman

University of Twente
The Netherlands



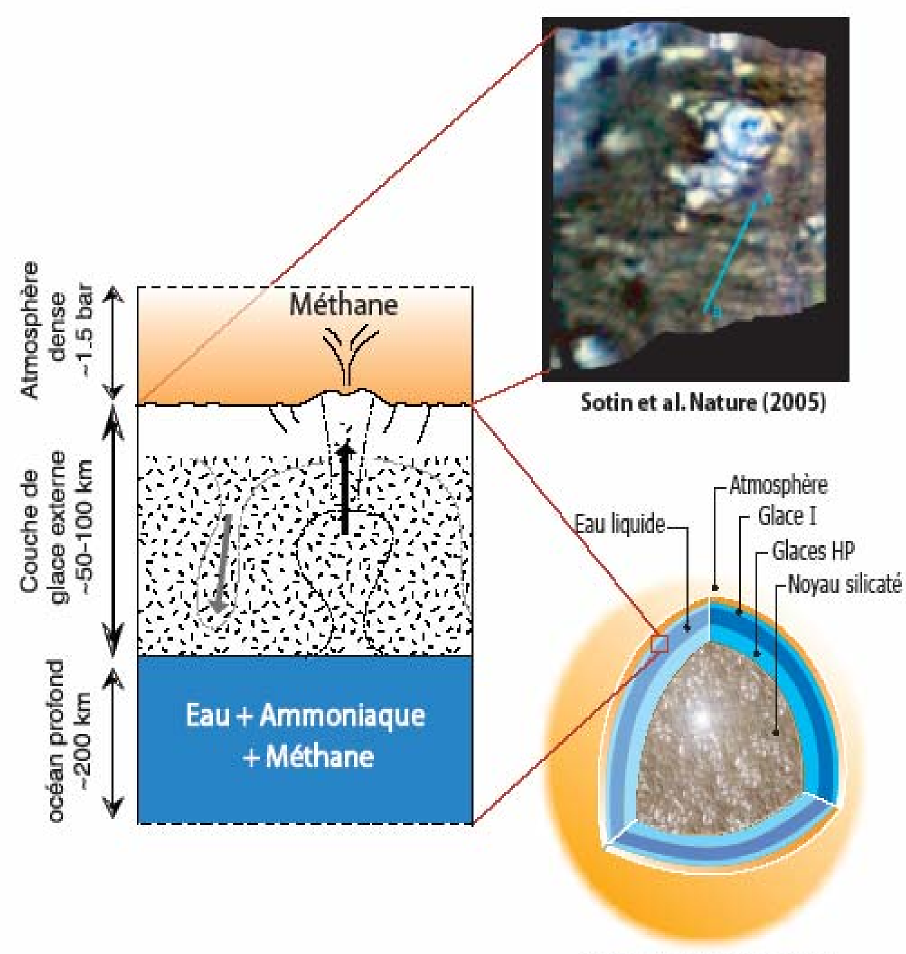
Outline

- Introduction
  - Sensitivity requirements
- Device design
- Sensitivities
  - Brownian / Thermal / Readout
- Conclusions



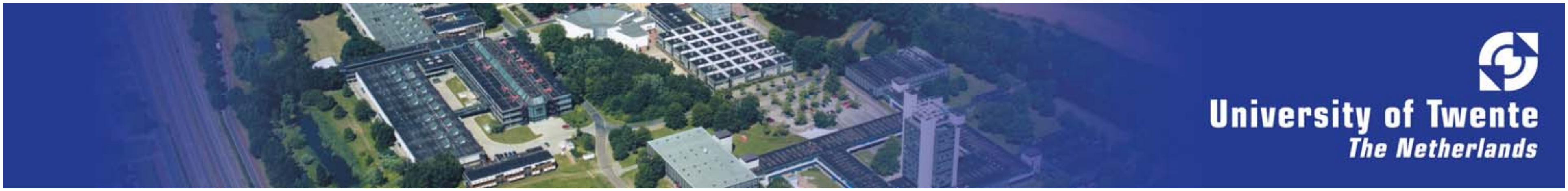
Gravity research topics

- Planets/moons
  - Local anomalies
  - Evolution of the planet/moon: global structure
- Combination with other measurements



Sotin et al. Nature (2005)

Tobie et al. Icarus (2005)



Basic equations

- Gravity potential describes the gravity field
- Differentiating this potential twice yields the gravity gradient as follows:

$$V\left(r,\theta,\phi\right)\rightarrow\vec{g}\rightarrow\Gamma$$

- The unit of gravity gradient is Eötvös (E): 1E = $10^{-9}/s^2$
- Gravity potential over a surface is described with spherical harmonics:

$$V\left(r,\theta,\phi\right)=\sum_{n=0}^{\infty}\sum_{m=0}^{m}\frac{GM}{a}\left(\frac{a}{r}\right)^{n+1}\left(A_n^m\cos\left(m\phi\right)+B_n^m\sin\left(m\phi\right)\right)P_n^m\left(\theta\right)$$

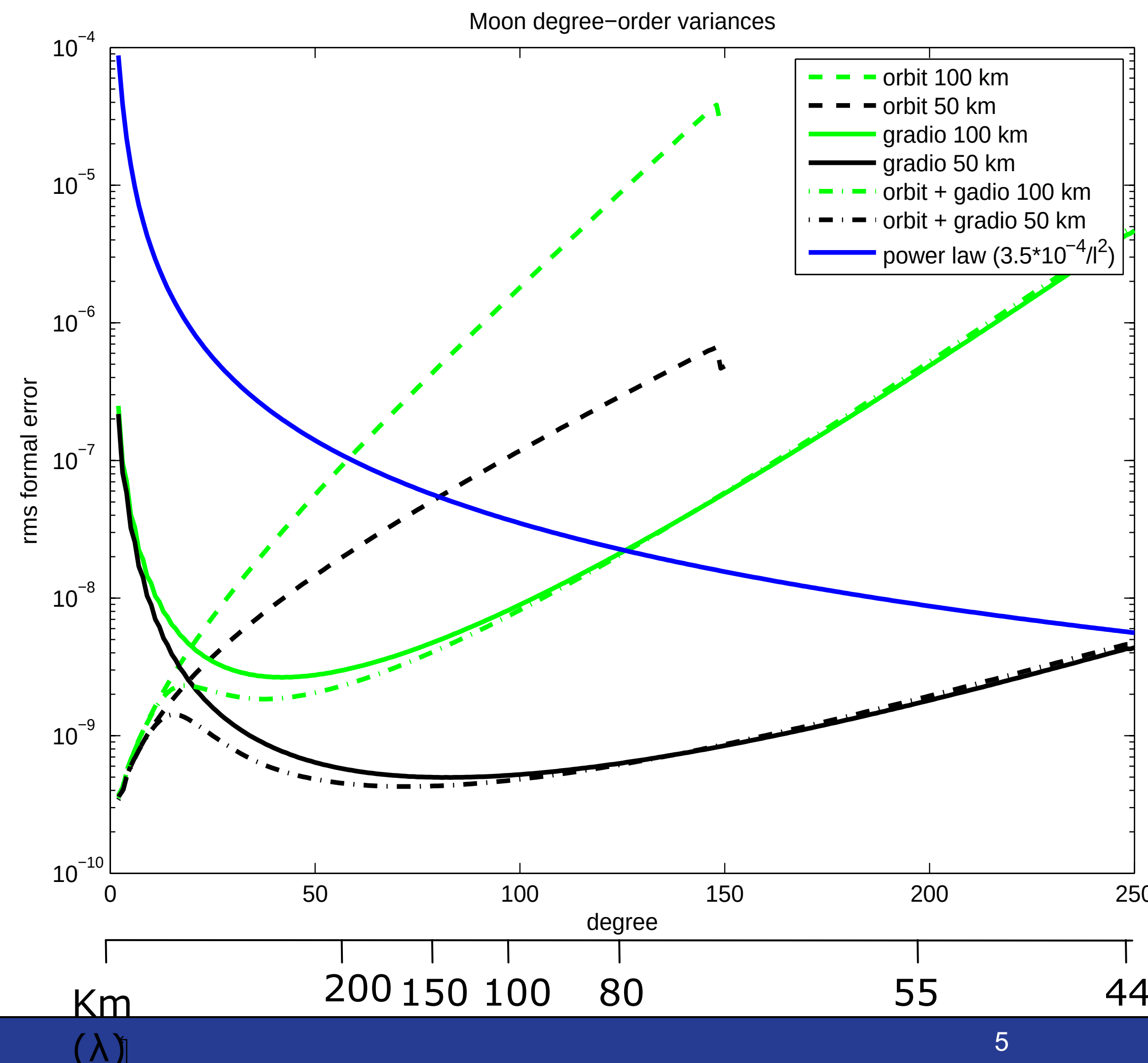
With P the associated Legendre polynoms, n order, m degree

- Higher orders describe the details

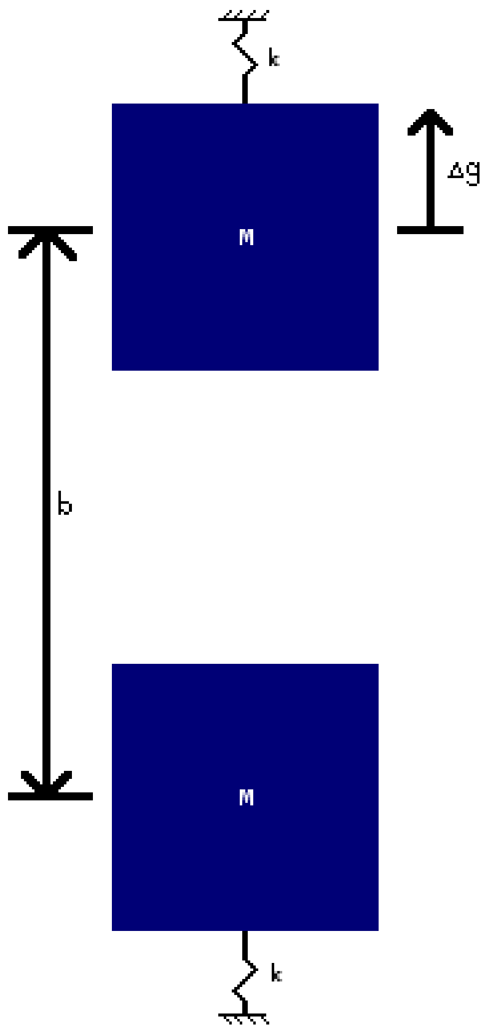
Sensitivities needed for Moon

At least 1E/rtHz
is needed

T = 1 yr
1 repeat
σ_{orb} = 1 m/√Hz
σ_{grad} = 1 E/√Hz
sampling = 1 Hz
V_{zz} only
MB = 0.001 – 1 Hz



Power spectral density of gravity gradient sensors



$$S_\Gamma = \Gamma_n^2 = \frac{8}{mb^2}\left(\frac{k_b T\, 2\pi f}{Q(f)} + \frac{(2\pi f_0)^2}{2\beta\eta}\varepsilon_A(f)\right)$$

Here:

b is the base line between the two probe masses

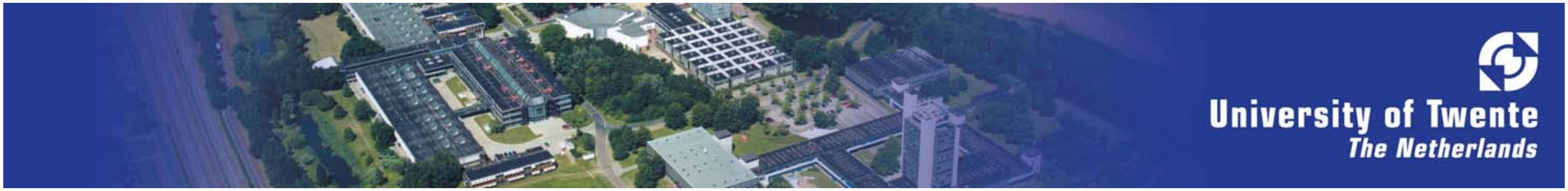
m is the probe mass

f_o is the mechanical resonance frequency of the differential mode

Q is the quality factor of the resonance mode

$\beta\eta$ is the energy coupling factor of the sensor

ε_A is the sensor noise energy



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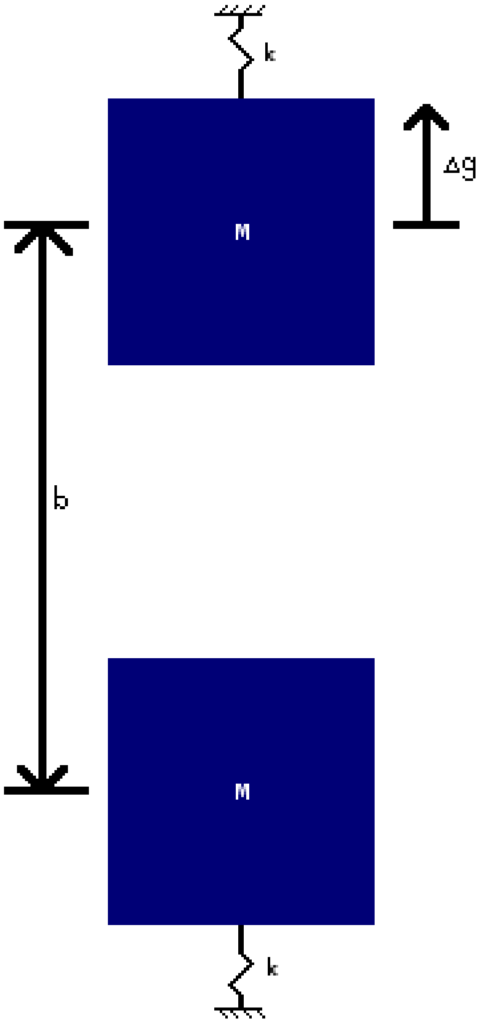

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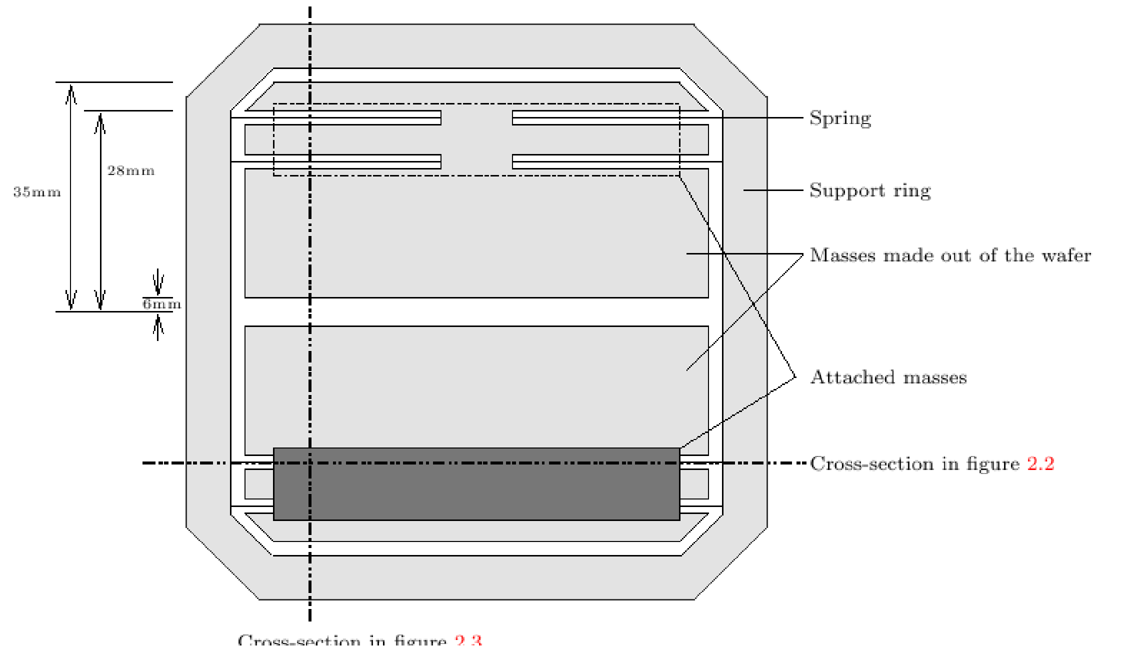
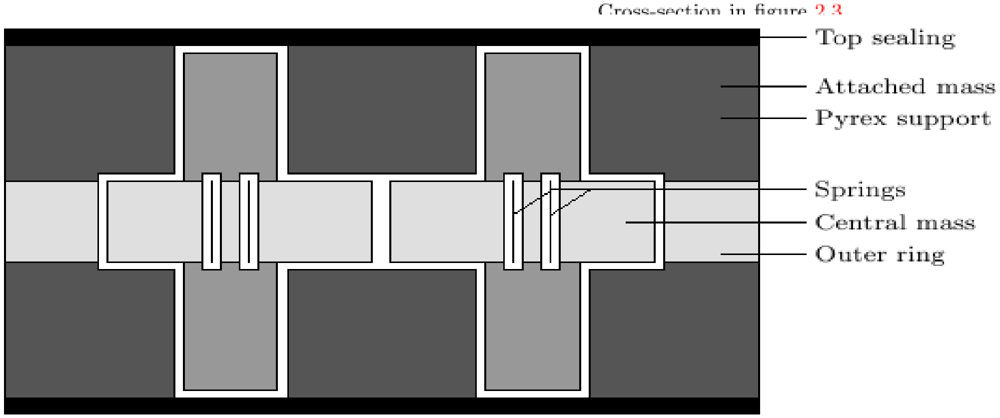
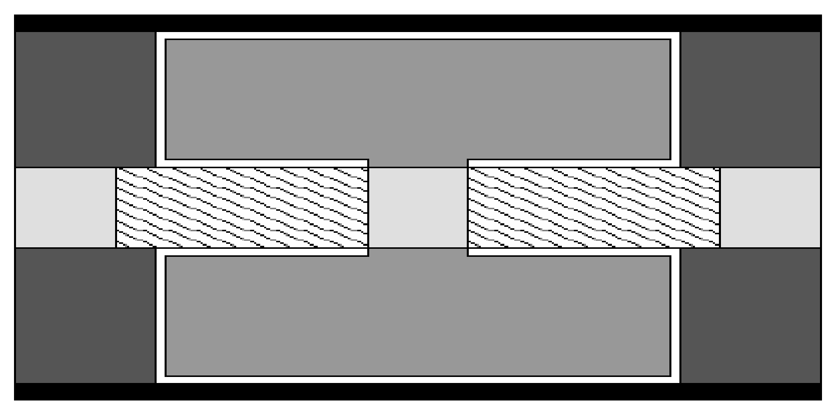
- For a good gradiometer mass and baseline should be big
- For use on a satellite, mass & size must be small

Miniaturization needed --> MEMS

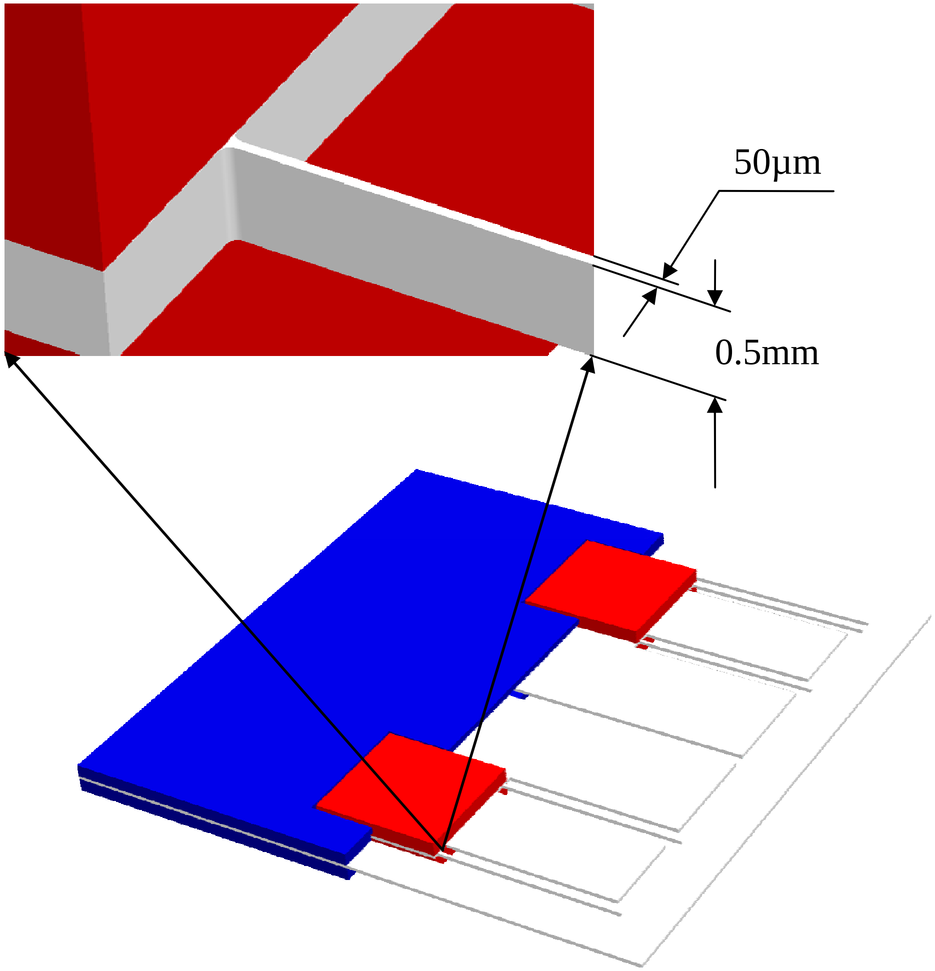
MEMS – Concept design

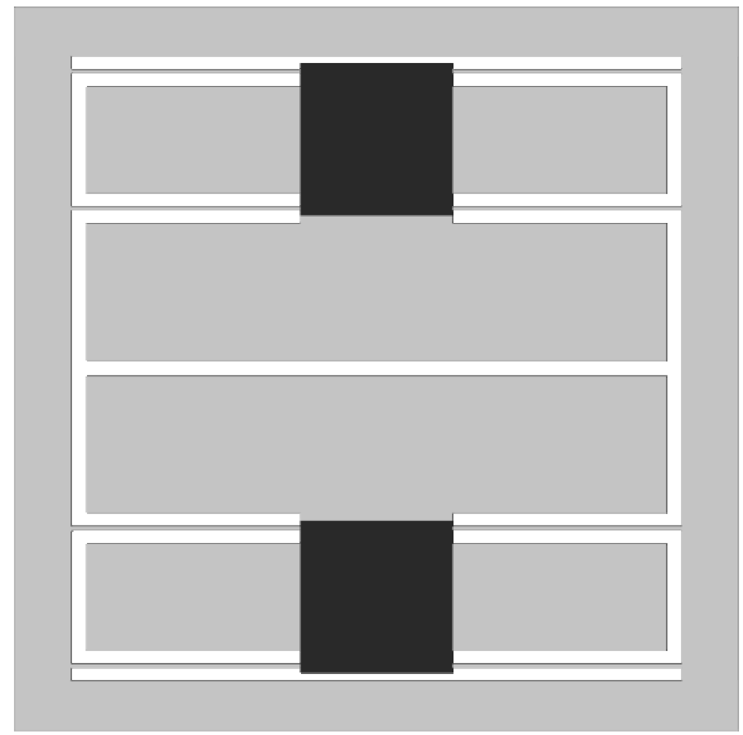


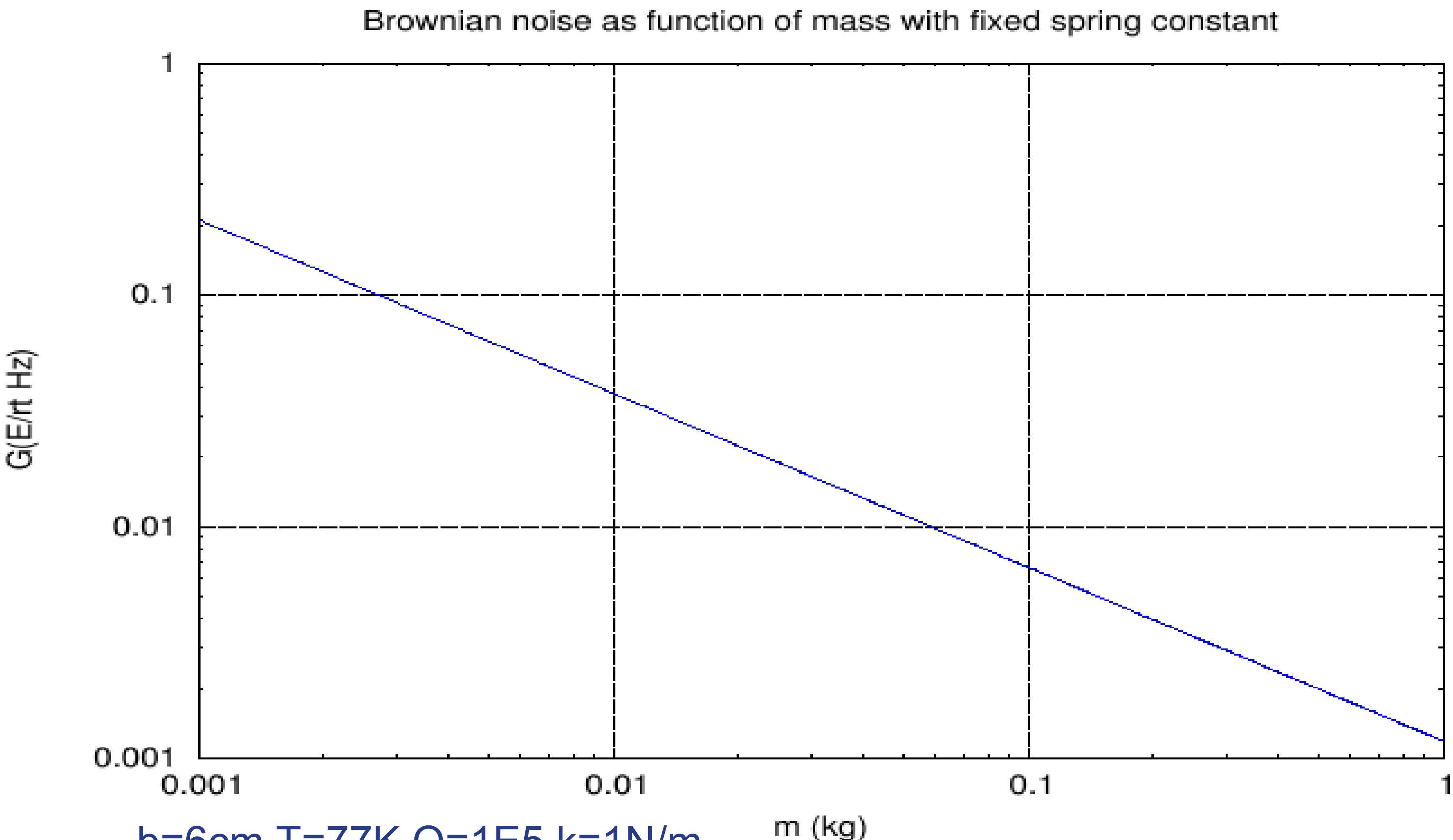




MEMS – Concept design



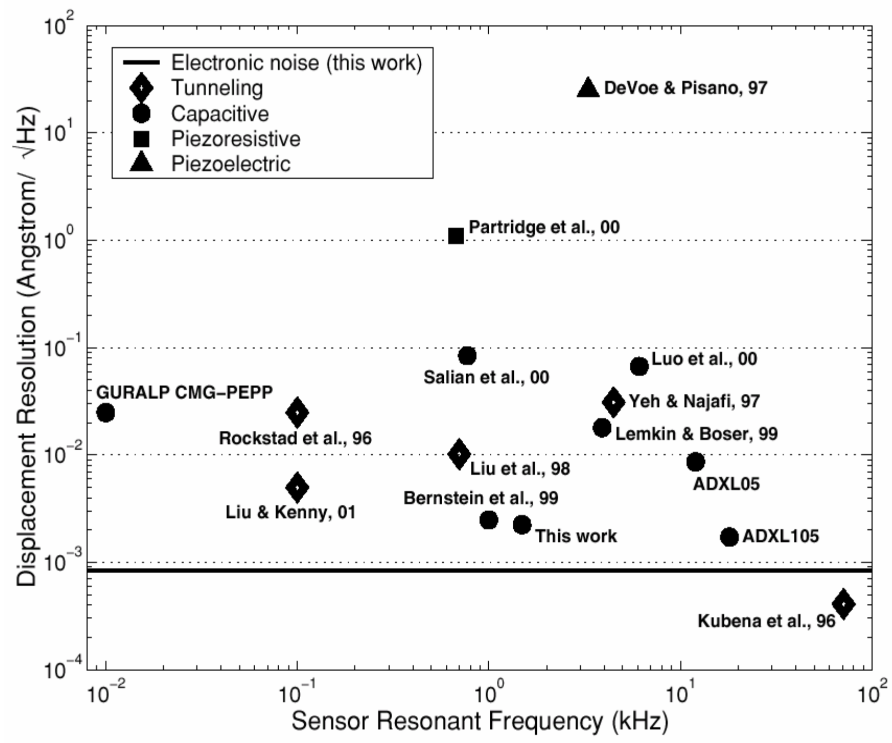




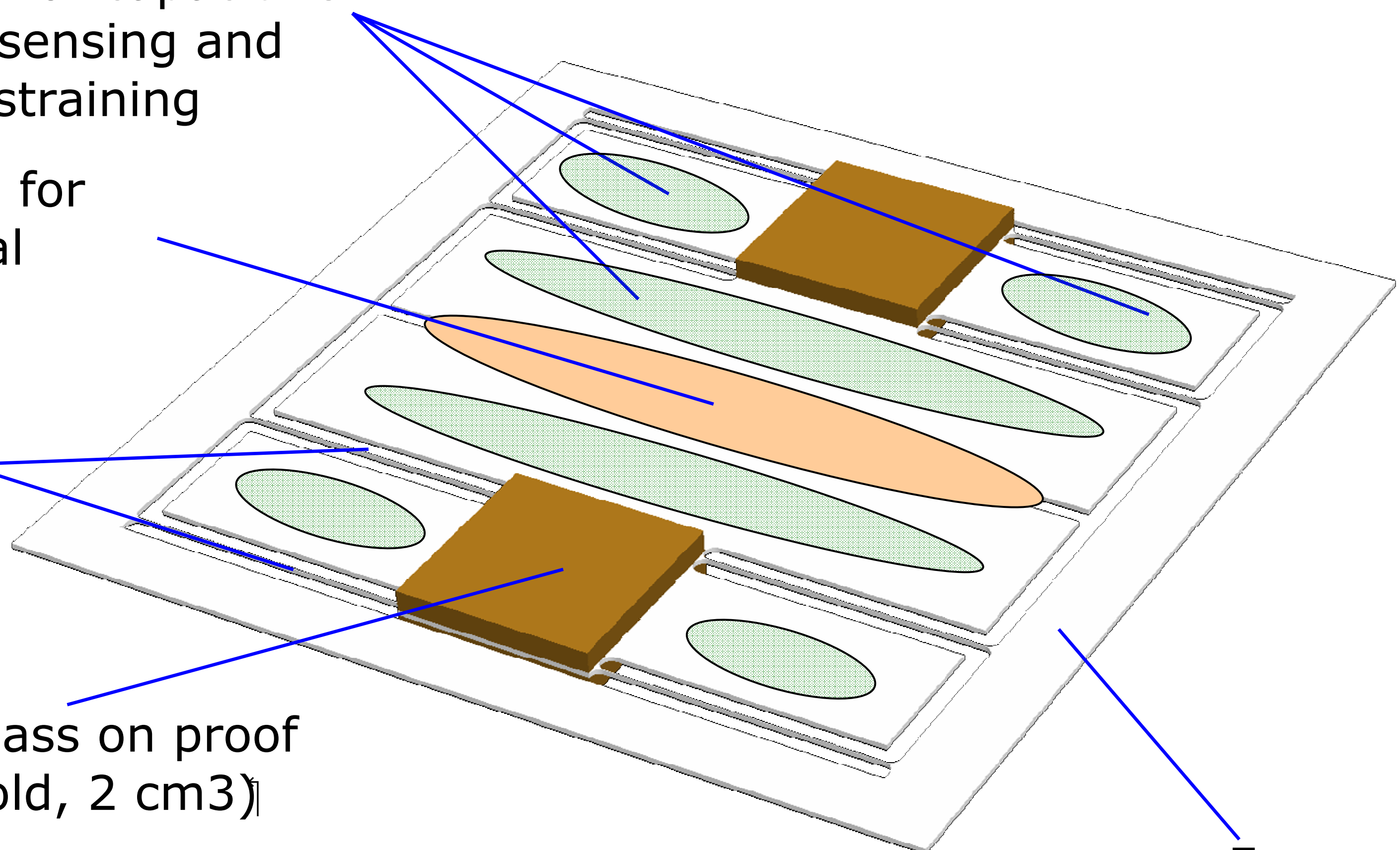
b=6cm,T=77K,Q=1E5,k=1N/m

Readout – capacitive

- Possibility to detect small deflection has been shown in literature: 10-13m/s2/√Hz
- Relative easy integration with mechanics
- Same components for actuation, which means:
  - Readout also applies force to masses!
  - Same type of plates used for force feedback



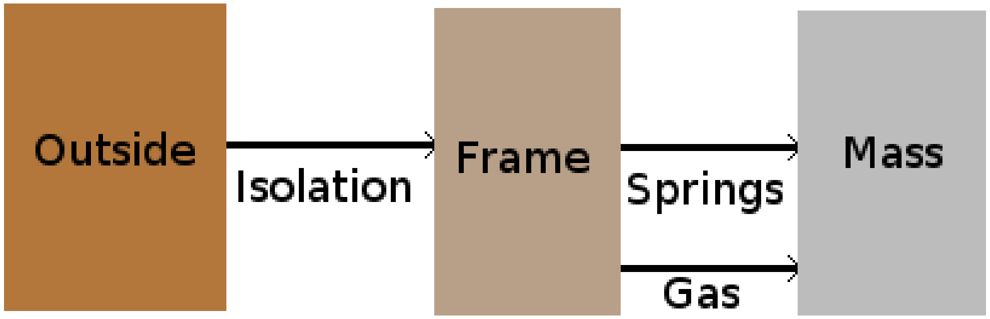
MEMS – Capacitive sensing & actuaction

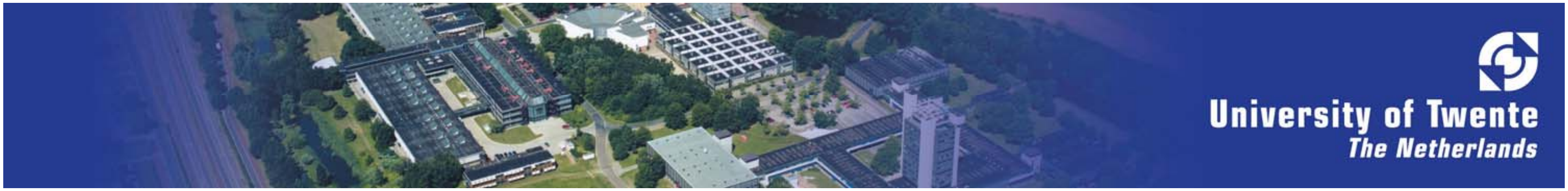


Thermal influences

- "DC" heating of the sensor: $T_{mass} = T_{frame}$
  - Everything expands, C change negligible

- Dynamic heating: $T_{mass} \neq T_{frame}$
  - Frame moves relative to readout: distance between spring work point and readout is important





Calculation of model

Springs: l x b x h = 6cm x 50um x 500um

kx=500kN/m, ky=1.38N/m, kz=138N/m

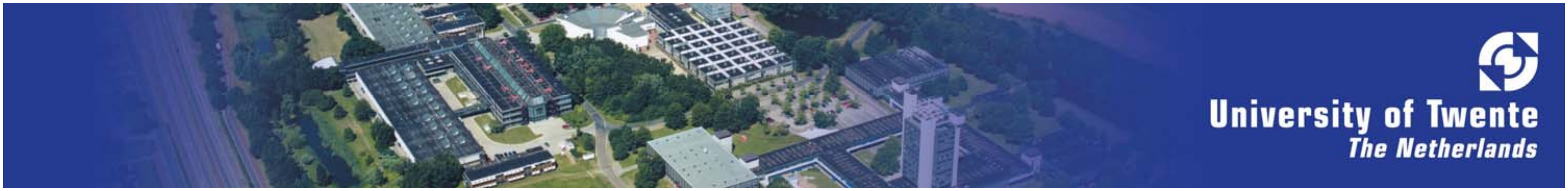
2 clamped-clamped-beam springs per acc.meter

Attached mass: Au: ρW= 19,300kg/m3

l x b x h = 1cm x 1cm x 1cm

Location: 3.25cm from center of sensor

Mass = 87g



Calculation of model

Q = 100,000

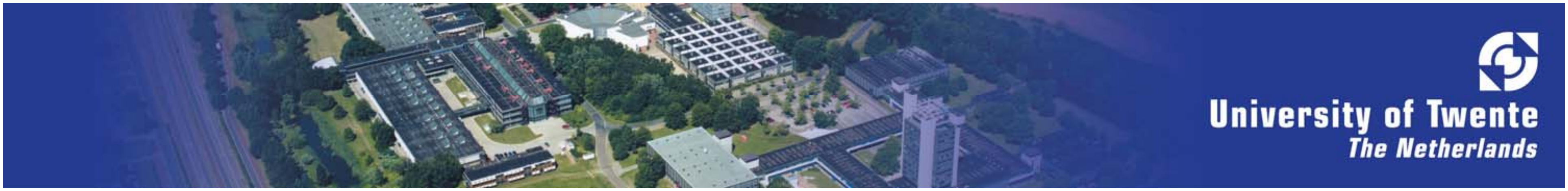
Readout: Δx = 10e-13 m/√Hz

Temperature: T=77K

Total mass: 87g

Frequency: 1Hz

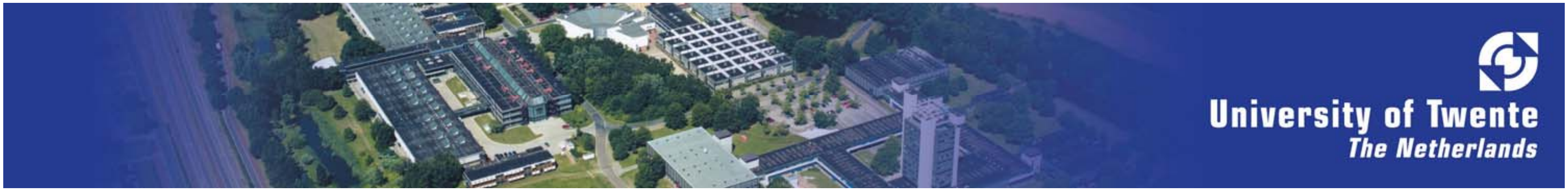
Baseline: 6.4cm



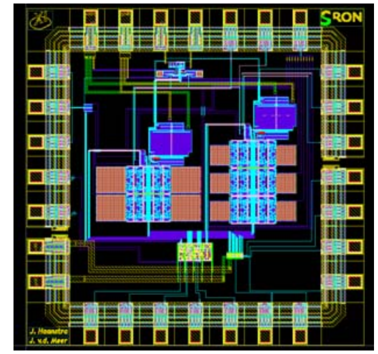
Calculation of model

Results:

Brownian	107mE√Hz
Readout	53mE√Hz
Total	119mE√Hz



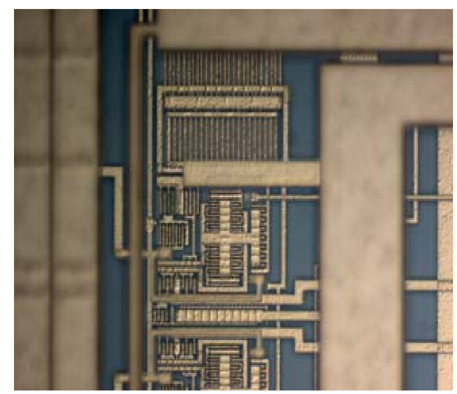
Electronics



Goal:

- Acquiring differential capacitance values
- Processing to get accelerations and gradients
- Providing feedback control to keep masses in workpoints
- Compensate for unmatched systems by using electronic negative springs

Electronics will be developed as ASIC (Application Specific IC) by SRON



Conclusions

- For planetairy missions: at least $1E/\sqrt{Hz}$ sensitivity needed
- Proposed design: $119mE/\sqrt{Hz}$ possible
- Systems need to equal to reject common mode accelerations
  - Negative spring constants can be used to control