

From an experimental idea to a satellite

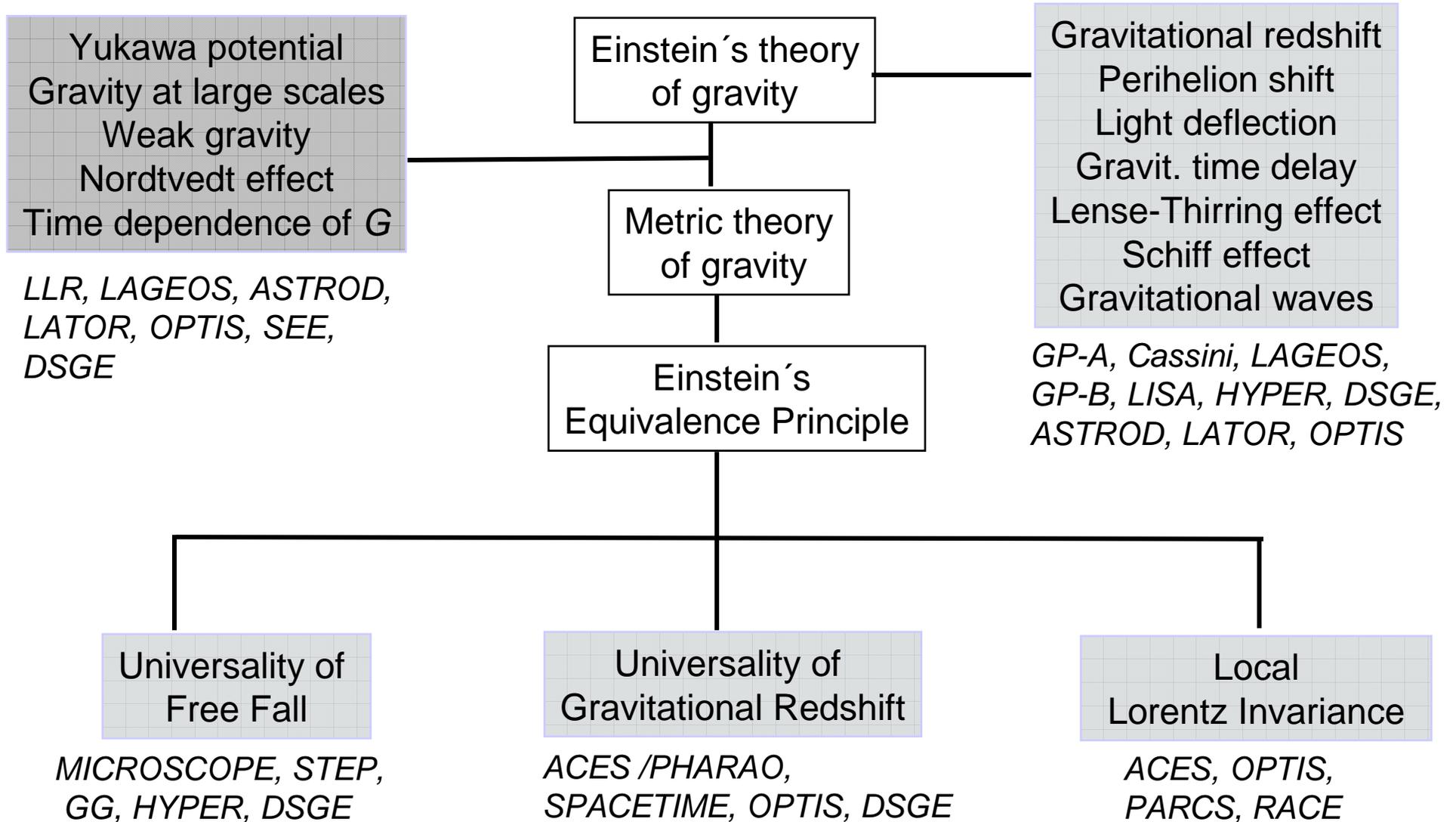
Hansjörg Dittus

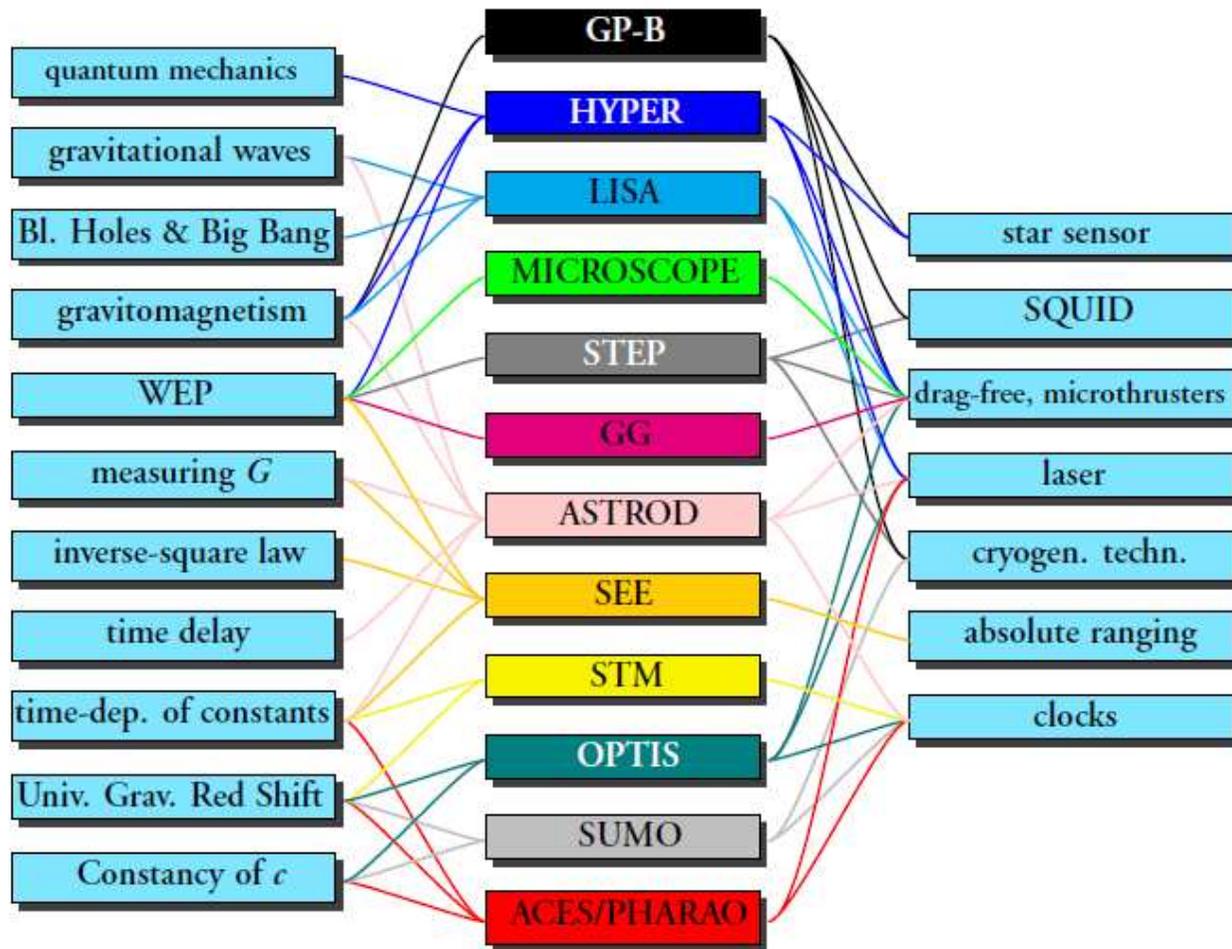
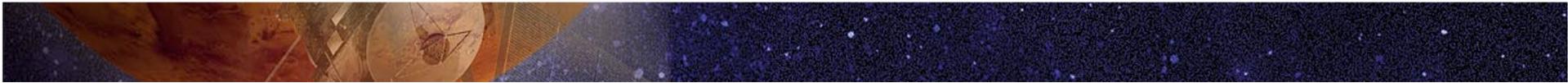
**Institute of Space Systems, Bremen
German Aerospace Center**

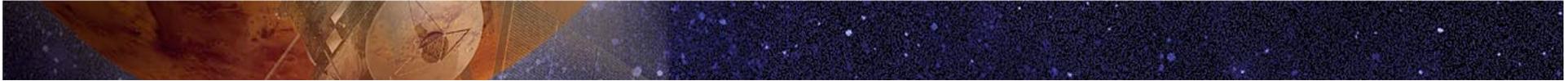


**Deutsches Zentrum
für Luft- und Raumfahrt e.V.**
in der Helmholtz-Gemeinschaft

Looking back in „History“



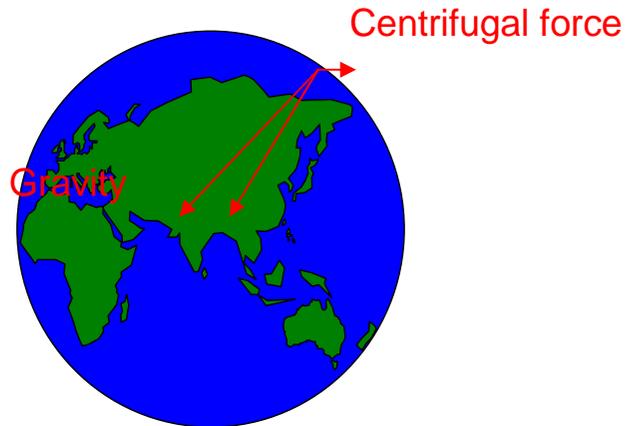




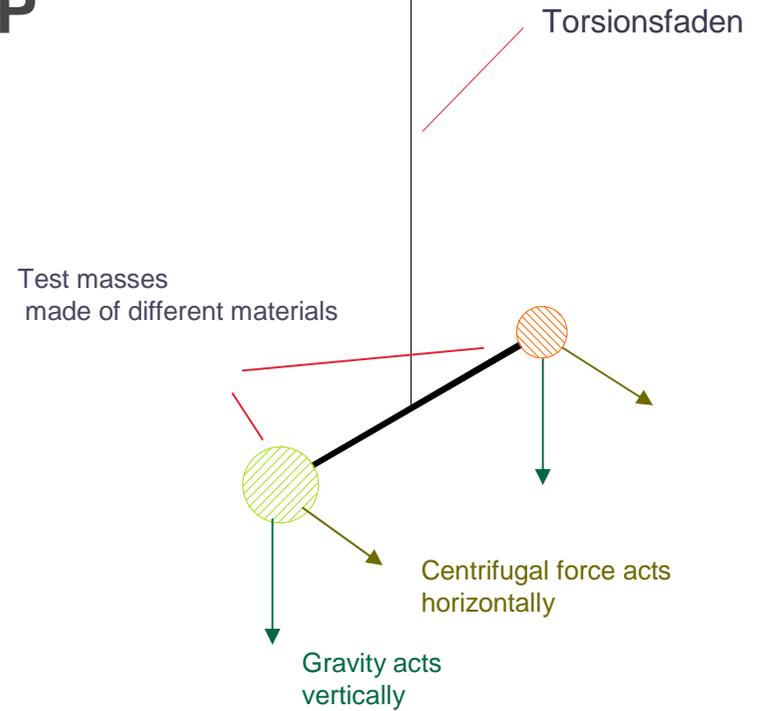
Everything outside the Solar System refuses to follow the laws of General Relativity.

Joao Magueijo, Imperial College

Why satellite experiments to test EP



Torsion balance uses only 0.3 % (earth mode) and 0.07 % (solare mode) of the inertial force wrt to earth gravity.

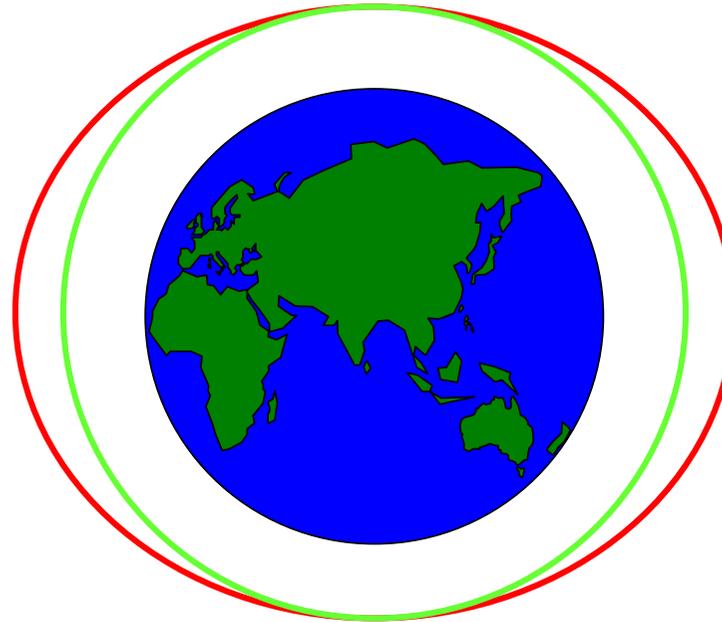
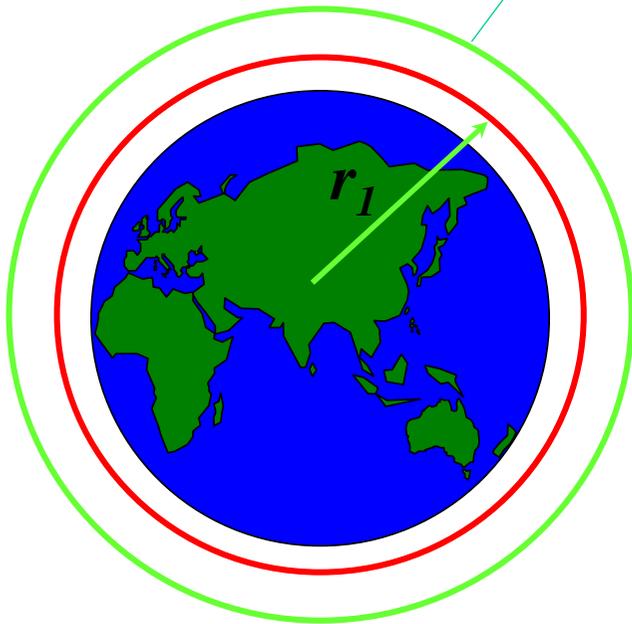


Periodic free fall in space..

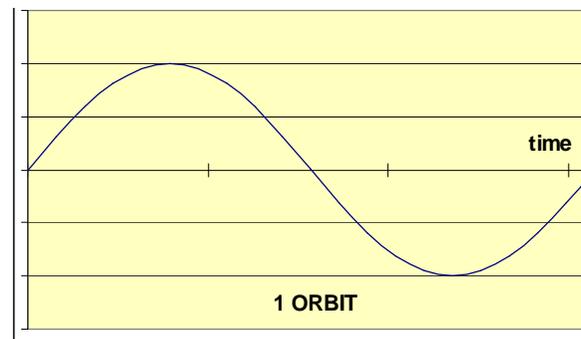
	Direct measurement (full signal)	Influence of torsion fibre	Periodic long term-experiment
Free fall experiment	Y (+)	N (+)	N (-)
Torsion balance experiment	N (-)	Y (-)	Y (+)

EP-Maasurement on satellite

$$dr = \frac{1}{3} r_1 \eta_E \approx 10^{-12} \text{ m}$$

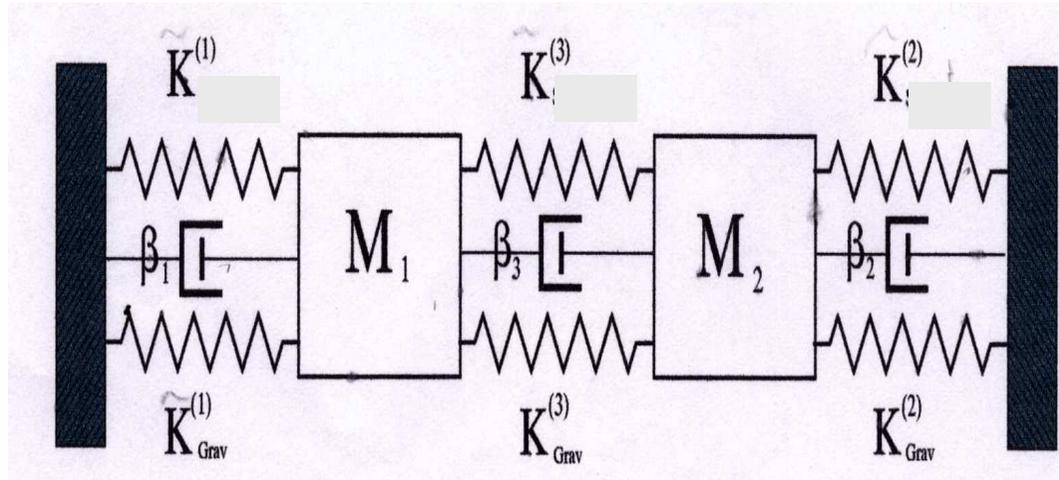


Differential orbit differences cannot be measured directly



Relative test mass position

Development of precise differential accelerometers



(1) Moveable test masses: $a \approx \left(\frac{k}{m} - \beta^2 \right) \cdot \delta x$

$\beta = 0$ and **weak** k : high resolution position sensor

Problem: Complicated test mass movement

(2) Closed loop control:

$$a \approx a_{control}$$

$$\omega_{testmass} = \sqrt{\left(\frac{k}{m} - \beta^2 \right) + \left(\frac{k_{control}}{m} - \beta_{control}^2 \right)}$$

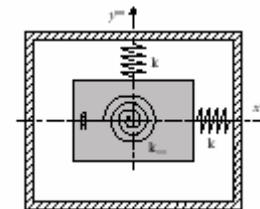
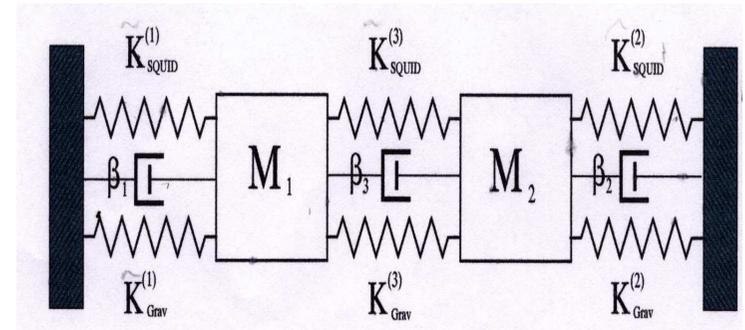
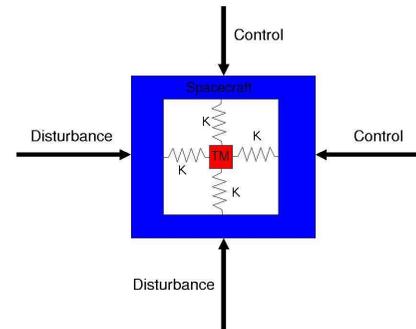
Stiffness can be much higher than k : large bandwidth, but lower resolution

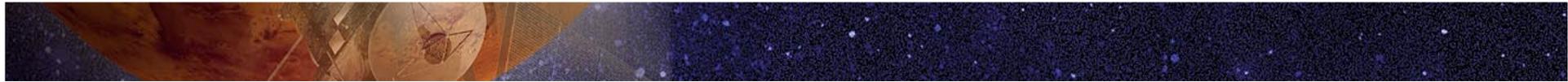
Problem: back-action by noise

Drag-free AOCS for satellites

Concepts:

- (1) **Closed loop control**
large bandwidth
two test masses: aligned
e.g. MICROSCOPE
 10^{-7} m / s^2 at $8 \cdot 10^{-4} \text{ Hz}$
- (2) **Open loop for two moveable test masses (aligned)**
very small bandwidth
- (3) **Virtual reference point for more than one test mass**
 10^{-14} m / s^2 at 10^{-3} to 10^{-4} Hz
- (4) **„Free floating“ control for more than one test mass misaligned**
needs multiple parameter control



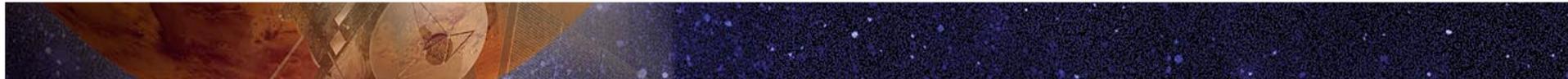


Drag forces and torques (for 1.5 m² cross area)

- **Atmospheric drag**
 - Linear drag: ca. 1mN
 - Torque: 10 $\mu\text{N} \cdot \text{m}$

 - **Radiation pressure by Earth albedo**
 - Linear drag: ca. 10 μN
 - Torque: 1 $\mu\text{N} \cdot \text{m}$

 - **Magnetic torque (interaction with Earth magnetic field)**
 - Torque: 100 $\mu\text{N} \cdot \text{m}$
 - After torque compensation: 10 $\mu\text{N} \cdot \text{m}$
-
- **Solar radiation pressure**
 - Linear drag: ca. 10 μN
 - Torque: 1 $\mu\text{N} \cdot \text{m}$



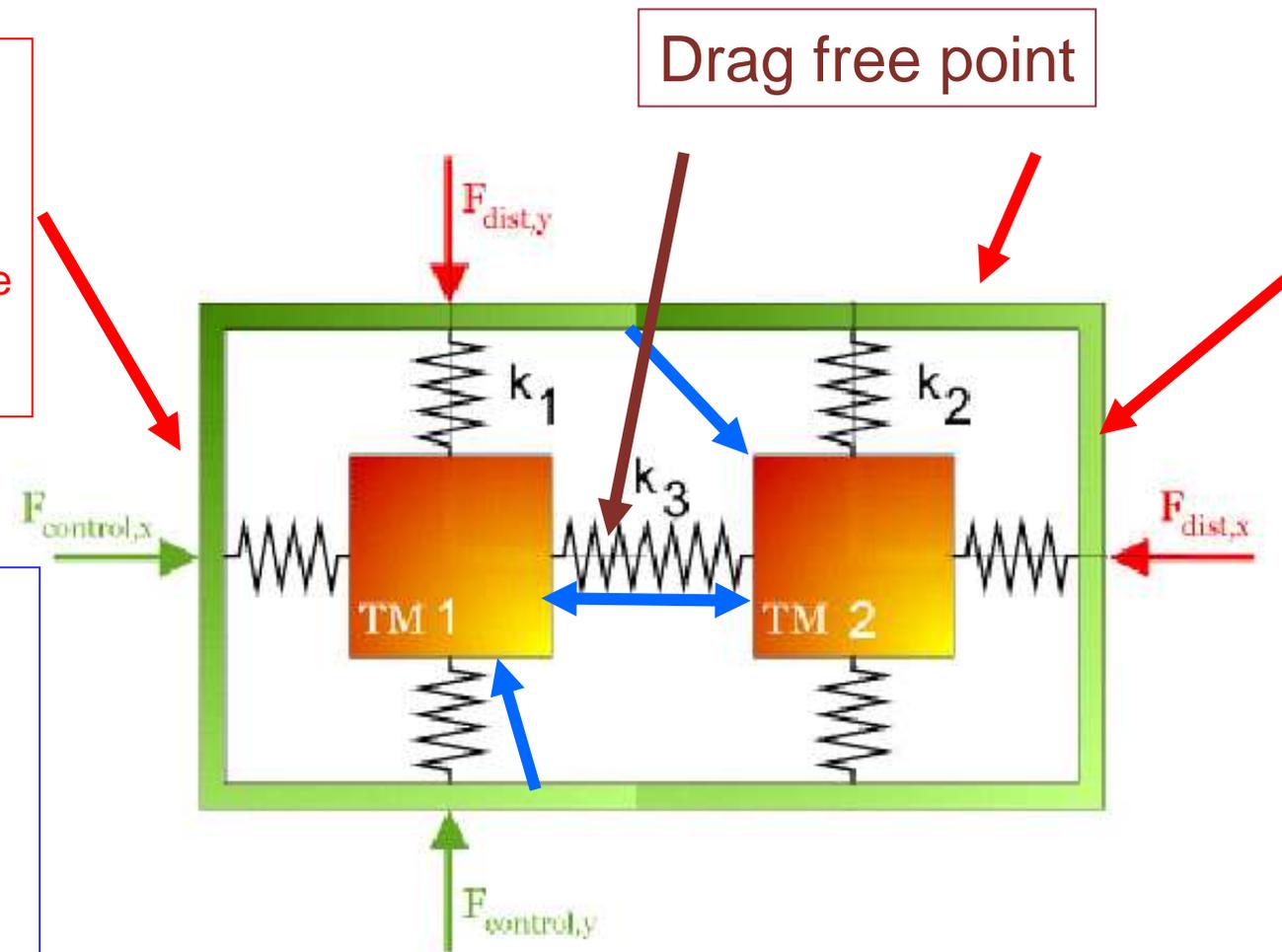
Two-test-mass problem

external perturbations

- Air-drag
- Radiation pressure
- Magnetic fields
- Solar wind, etc.

internal perturbations

- Patch effects
- Radiometer effect
- Non-perfect shielding etc.



⇒ Huge complexity of signal !

Low thrust propulsion systems

Balancing drag forces and torques

- Atmospheric drag
 - Linear drag: ca. 1 mN
 - Torque: 10 $\mu\text{N} \cdot \text{m}$
- Radiation pressure by Earth albedo
 - Linear drag: ca. 10 μN
 - Torque: 1 $\mu\text{N} \cdot \text{m}$
- Magnetic torque (interaction with Earth magnetic field)
 - Torque: 100 $\mu\text{N} \cdot \text{m}$
 - After torque compensation: 10 $\mu\text{N} \cdot \text{m}$
- Solar radiation pressure
 - Linear drag: ca. 10 μN
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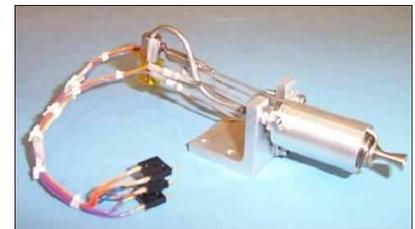
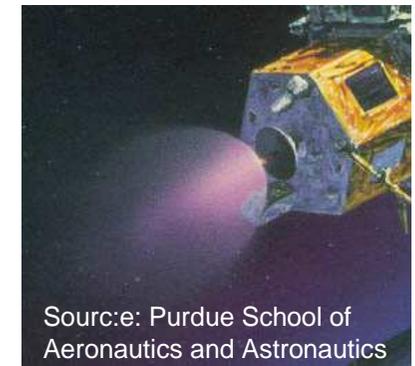
Propulsion system requirements:

Thrust control: $\Delta S < \pm 0.1 \mu\text{N}$

Residual acceleration:

$< 10\text{-}15 \text{ m}/(\text{s}^2 \cdot \text{Hz}^{0.5})$

Permanent operation



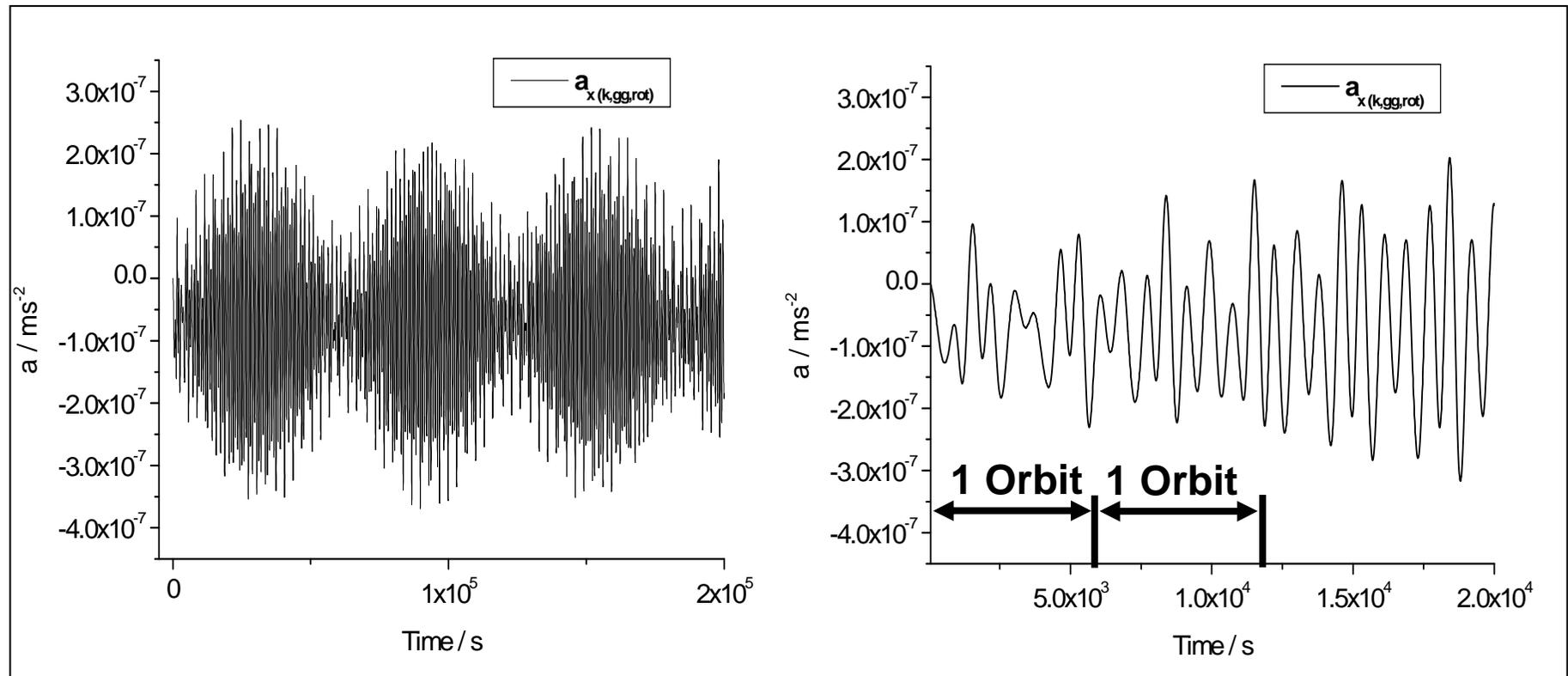
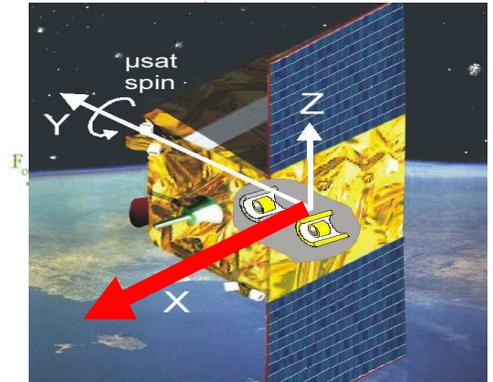
Simulation

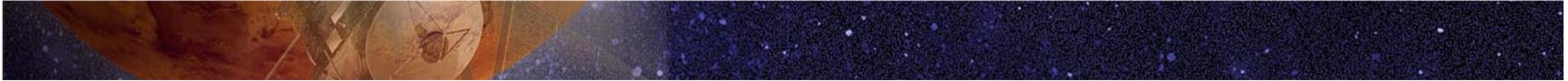
Example: differential acceleration of 2 test masses

Satellite orbit: ω_o

Test mass coupling: $\omega_k^2 = k/m$ $k_{typ.} = 5 \cdot 10^{-6}$ N/m

S/C spin rate: ω_{spin}



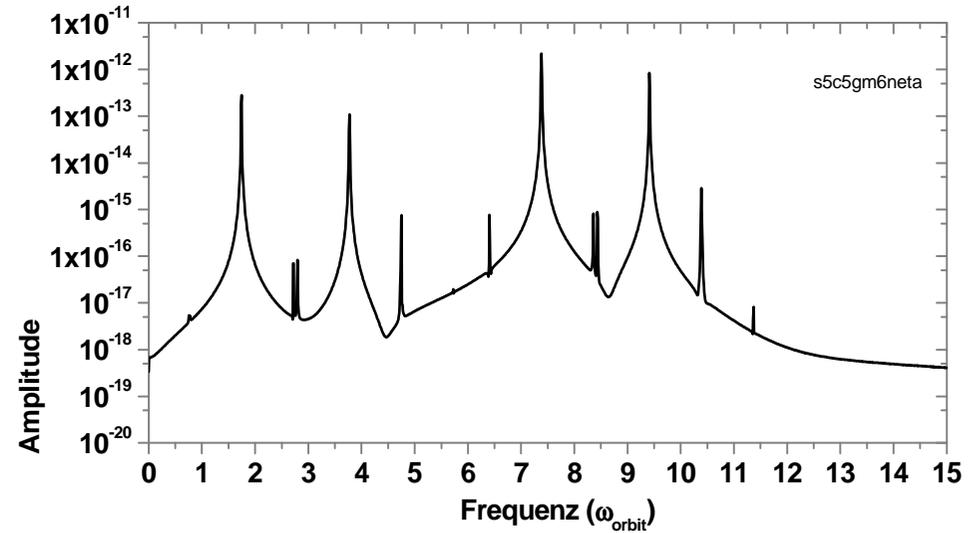


**EGM
6th order**

$$\omega_{\text{spin}} = 4.6\omega_o$$

$$\omega_k = 2.9\omega_o$$

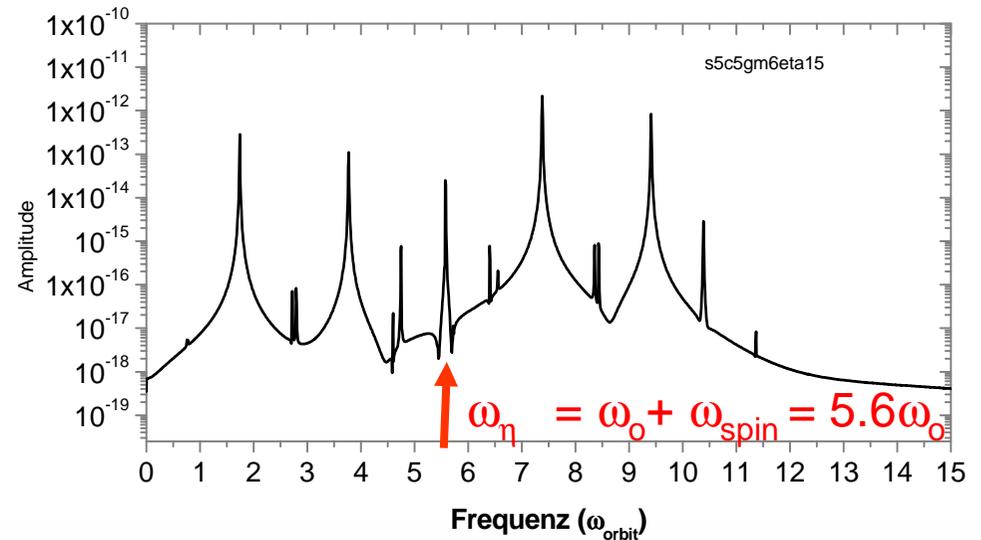
$$\eta = 0$$



$$\omega_{\text{spin}} = 4.6\omega_o$$

$$\omega_k = 2.9\omega_o$$

$$\eta = 10^{-15}$$



High Performance Simulation



➤ Objectives

- Provide comprehensive simulation of the real system including science signal and error sources
- Provide simulation environment for control system performance validation
- Generate data needed to test data reduction methods
- Provide capability for identification of the satellite and instrument

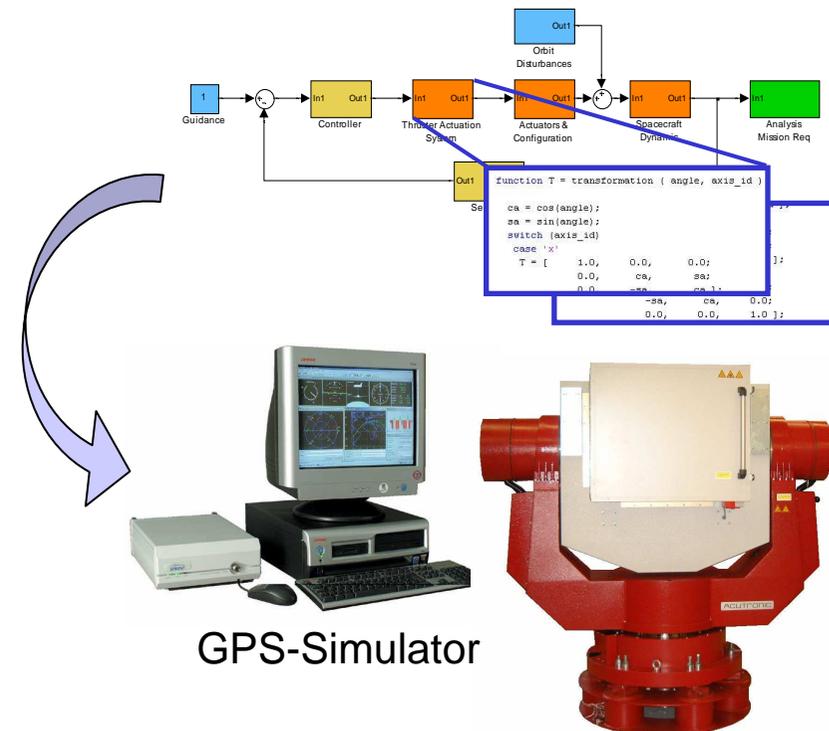
➤ Core features

- Simulation of full satellite and test mass/experiment dynamics in six degrees of freedom by numerical integration of the equations of motion
- Multi-body system
- Consideration of linear and nonlinear coupling forces and torques between S/C and TMs
- Modelling of cross-coupling interaction
- Earth gravity model up to 360th degree and order + solar system effects
- Gravity-gradient forces and torques
- 5th order Runge-Kutta numerical integration, Bulirsch-Stoehr, Euler-Cauchy
- Misalignment, displacements, attitude errors, coupling biases
- ...

Satellite Dynamics and Interface Experiment / Spacecraft

- Important problem in order to keep accuracy
- Needs modelling of all experimental components and S/C subsystems
- Combining thermal and mechanical requirements

- Simulation software
 - High precision models
 - Validation with flight data
- Hardware-in-the-Loop-Testbed
 - Modular design
 - Applicable to different missions
- Test facilities for AOCS components



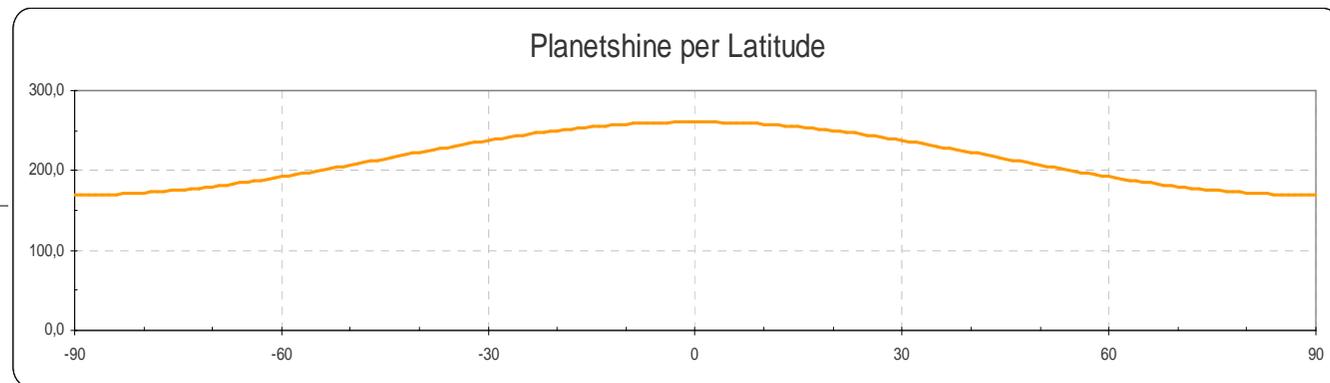
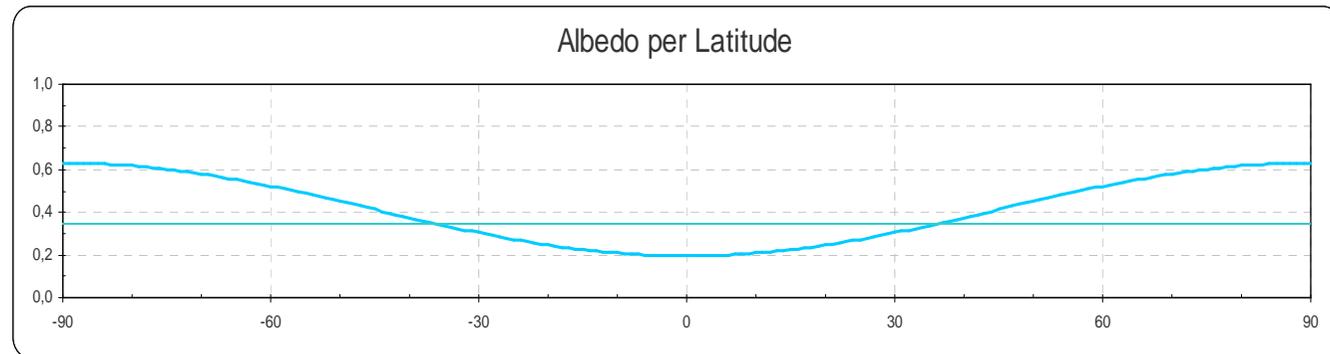
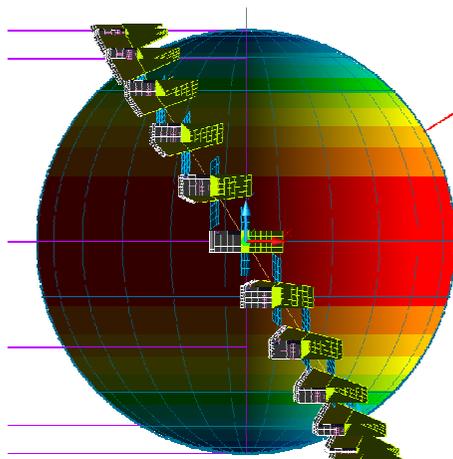
GPS-Simulator

3-Axis Rotation Table

Precise thermal models

- Albedo and Planetshine Earth Model
- Improved S/C thermal models: based on FEM

Planetshine Map



Südpol

Äquator

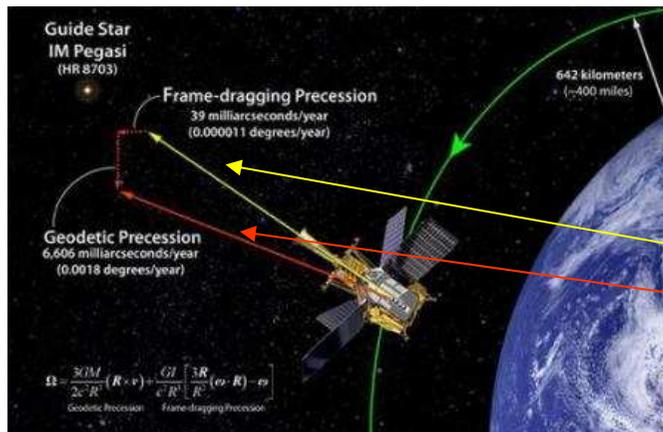
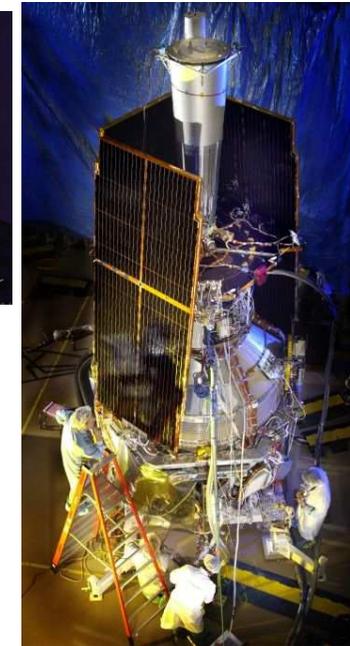
Nordpol

Mission Scenarios – Science Satellites

➤ Low earth orbit S/C

➤ Gravity Probe B

- Launched 19.4.2004 in a 642 km circular, polar orbit
- S/C mass: 3,145 kg
- Pointing accuracy: 0.2 arcs achieved by means of a Cassegrain telescope
- Residual acceleration requirement: $< 10^{-9} \text{ m}/(\text{s}^2 \cdot \text{Hz}^{0.5})$, achieved: $< 5 \cdot 10^{-11} \text{ m}/(\text{s}^2 \cdot \text{Hz}^{0.5})$
Use of gas proportional thrusters with He-boil-off)
- Use of gyroscopes (niobium coated exact silica spheres) with SQUID-based read-out

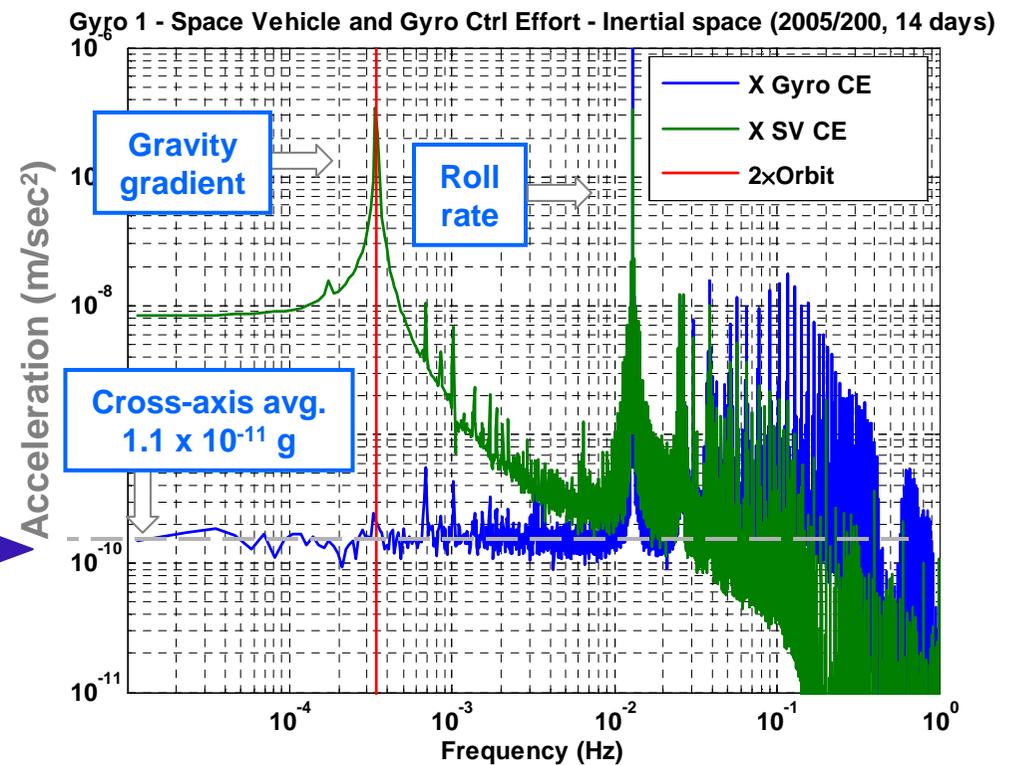
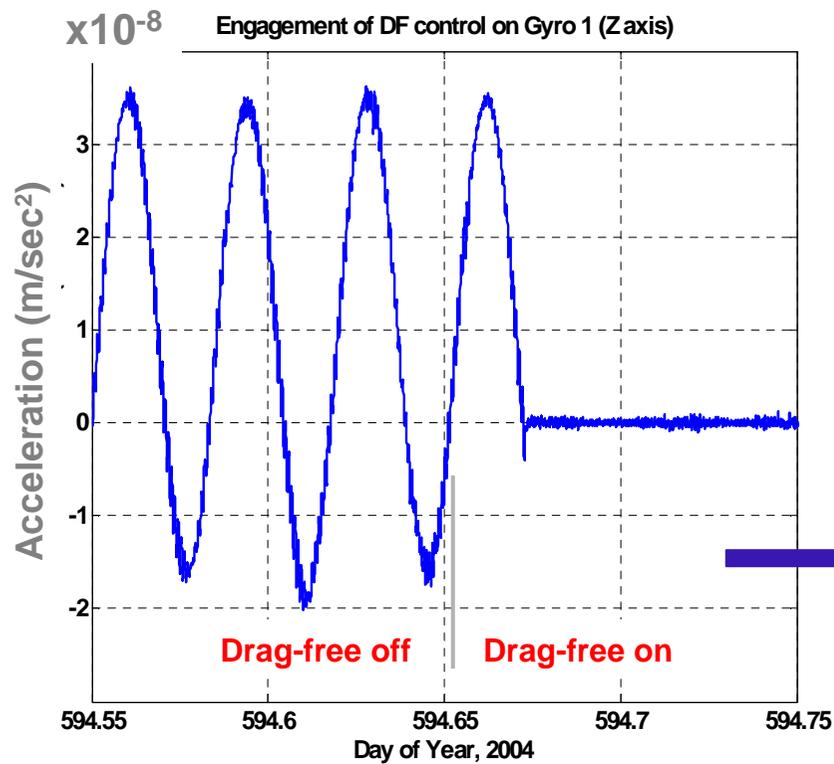


- Measurement of the precession of a gyroscope due to space-time curvature
- 6,6 arcsec per year by geodetic precession; confirmed within 0.5 %
- 0,041 arcsec per year due to frame dragging (Lense-Thirring precession), confirmed within 1%

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \left(-\frac{1}{2} \vec{v} \times \vec{a} + \frac{3}{2} \vec{v} \times \nabla U + \nabla \times \vec{h} \right) \times \vec{S}$$

Mission Scenarios – Science Satellites

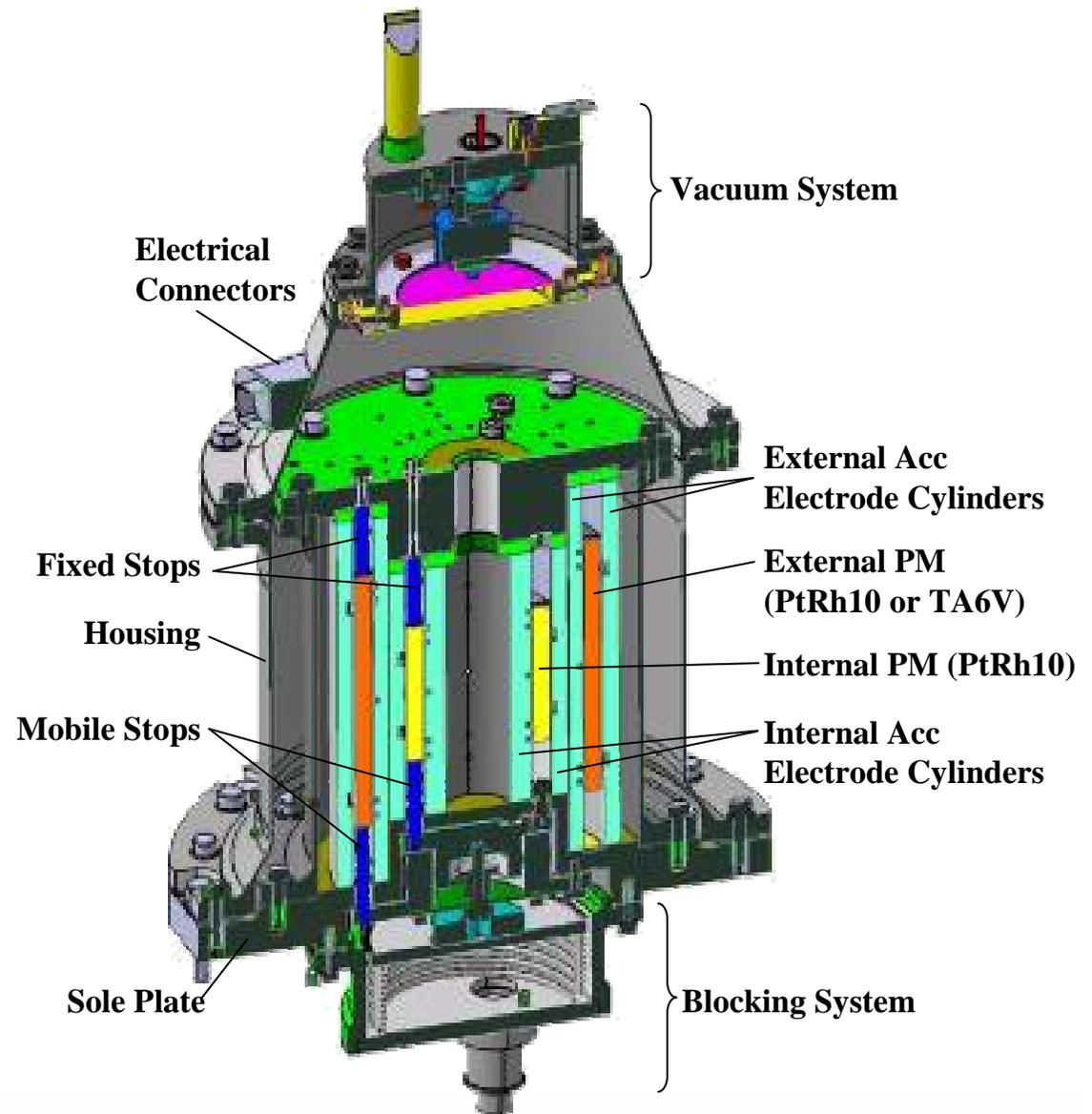
➤ Drag-free performance of GP-B

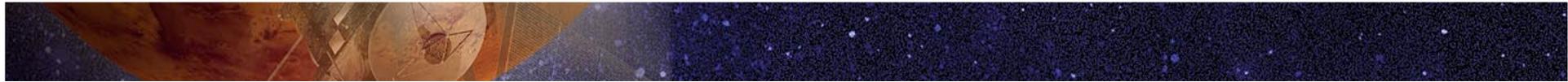


F. Everitt et al.

Machining

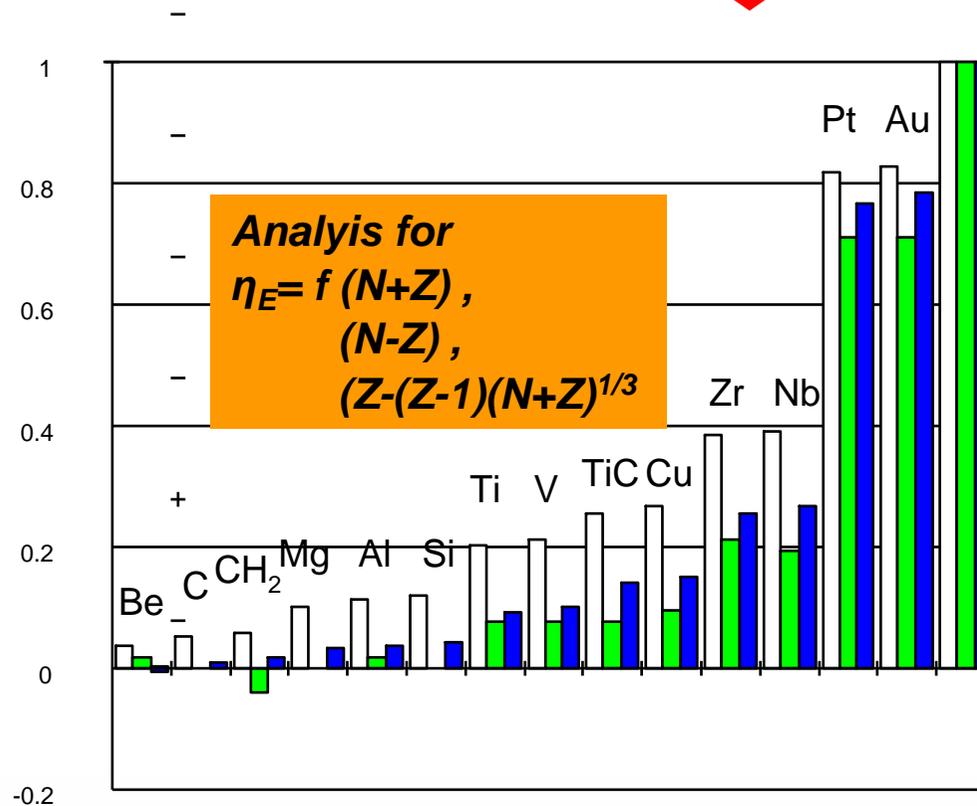
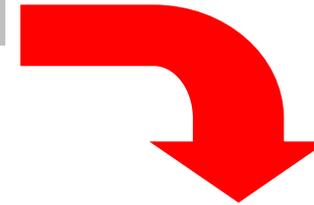
- Cylindrical test masse
 - Identical moments of inertia in all axes in order to minimize influences of the gravity gradient
 - High precision alignment
- Gold coating of the zerodur-structures and electrodes
- Blocking system for test masses during launch
- Ultra high vacuum
- Magentic shielding



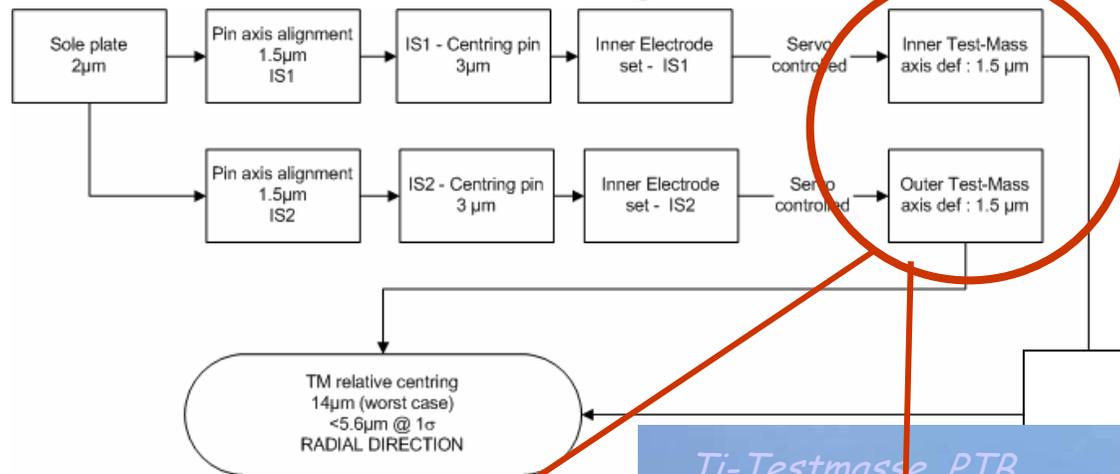


Test mass selection and machining characteristics

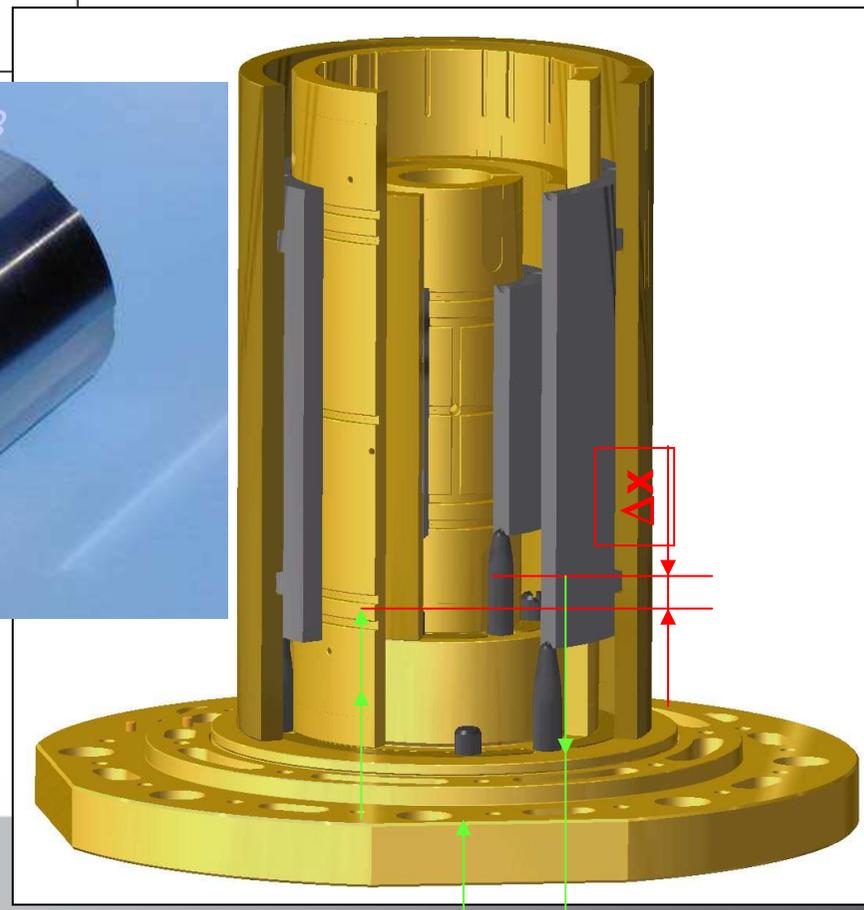
$$\eta = -(\gamma - 1) \left(c_{\text{baryon}} \left(\frac{N + Z}{\mu_{\text{Atom}}} \right) + c_{\text{lepton}} \frac{N - Z}{\mu_{\text{Atom}}} + 0.9430 \cdot 10^{-5} \frac{E}{\mu_{\text{Atom}}} \right)$$

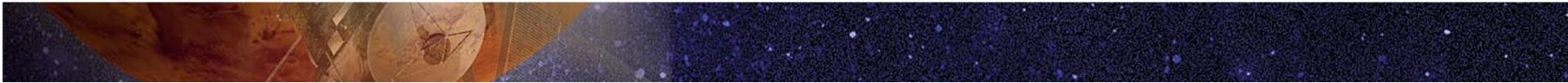


Test mass machining and tolerances



- Machining precision in all axes: 1.5 µm
- Misalignment along symmetry axes dependent on:
 - Maching accuracy (12µm worst case)
 - Capacitive metrology due to test mass conicity (worst case 17µm, 8.5µm due to improved metrology)

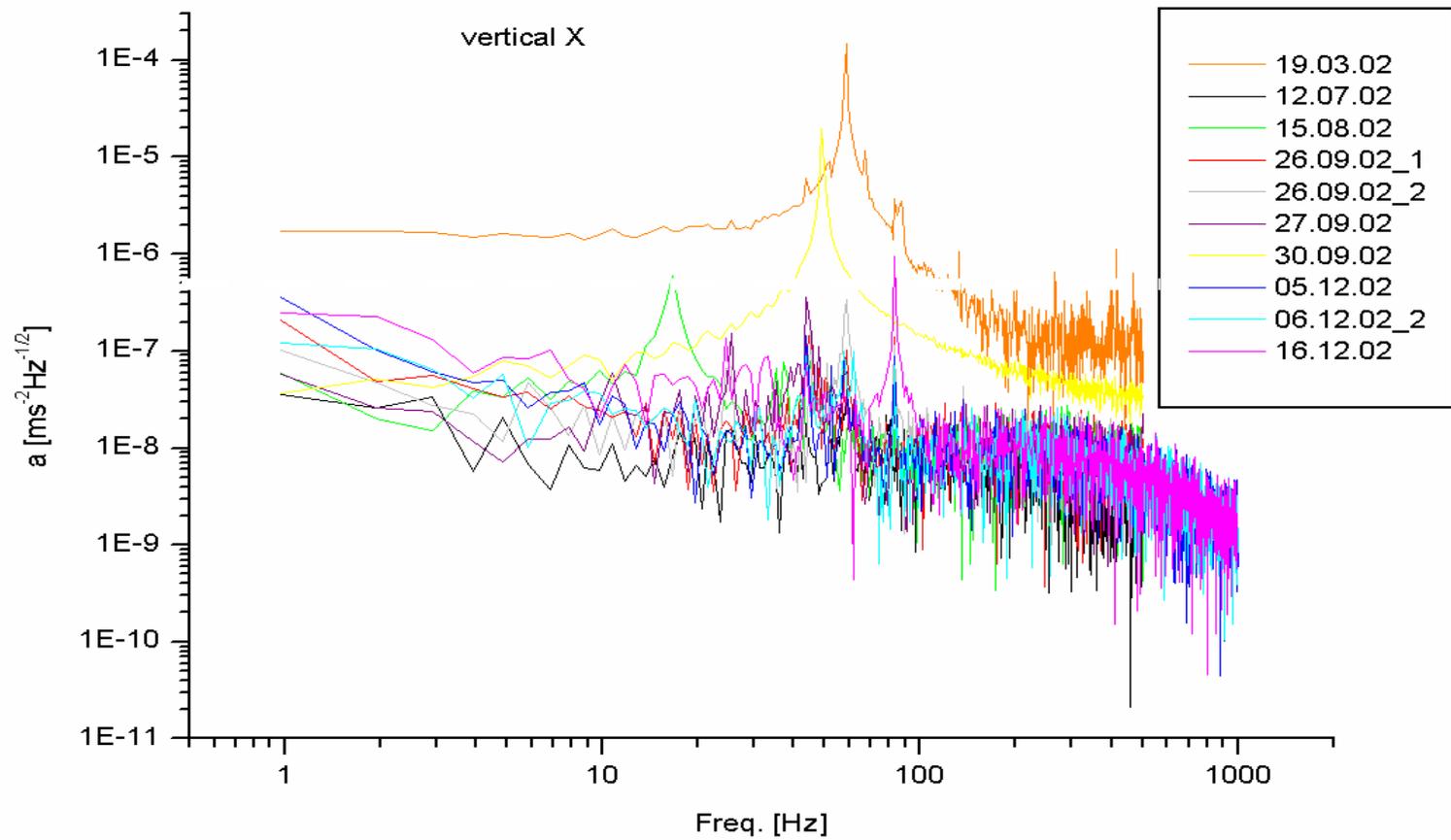


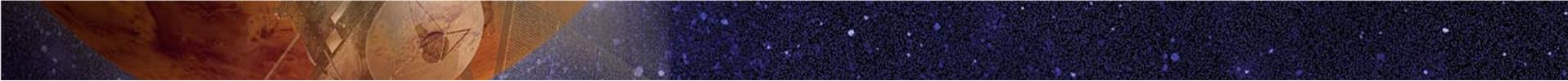


Test and verification environment



with free flyer





Conclusion

- Extremely challenging space experiment
- Various innovative space technology developments:
 - S/C AOCS of highest precision („no moving parts“)
 - S/C dynamic simulation
 - Low thrust propulsion
 - Thermal modelling
- Differential accelerometers
- Machining on sub μm -level
- Coating of non flat surfaces

- Stimulus for many new mission concepts:
 - LISA
 - STAR / OPTIS
 - STE-QUEST
 - X-ray telescope missions
 - GRACE-Follow-on
 - Earth observation on high precision level