"The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,..., as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),..., as the ratio of the forces which act upon them in the same gravitational field (gravitational mass). The equality of these two masses, so differently defined, is a fact which is confirmed by experiments...

The possibility of explaining the numerical equality of inertia and gravitation by the unity of their nature, gives to the general theory of relativity, according to my conviction, such a superiority over the conception of classical mechanics..."

A. EINSTEIN The Meaning of Relativity, Princeton,
“The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,...,
as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),..., as the ratio of the forces which act upon them in the same gravitational field (gravitational mass).
The equality of these two masses, so differently defined, is a fact which is confirmed by experiments...
Equivalence Principle

- Quantum Theory, Standard Model
  Electromagnetism, Strong & Weak Nuclear Force
- Geometric Theory of Gravitation, GR

→ Super Symmetry requires new particles...
→ Super String Theory, Branes... requires new field...
⇒ Galaxy rotation → Dark matter ? 25%
⇒ Universe Expansion acceleration → Dark Energy ? 70%

Domain of validity for current theories to be always confirmed more accurately

Many proposed space experiments:
- Lorentz Invariance test : PHARAO, LATOR,...
- Post-Newtonian Parameters accurate determination : GPB, PHARAO,...
- Determination and observation of relativistic effects : GPB, LISA, ASTROD, ...
- Stability of ‘Constants’

Equivalence Principle Tests (by UFF test) directly verify a fundamental basis of our present Gravity knowledge & may confirm dilaton existence

The possibility of explaining the numerical equality of inertia and gravitation by the unity of their nature, gives to the general theory of relativity, according to my conviction, such a superiority over the conception of classical mechanics...”

A. EINSTEIN The Meaning of Relativity, Princeton,
A Mission concept relying on best current technologies and models

DEMETER launched in 2004

GRACE EM & GOCE FM acceler., during qualification tests 06

CNES micro satellite

ONERA Accelerometer

OCA Space Geodesy & Astrometry

ESA FEEP

GRACE EM & GOCE FM acceler.
GOCE FM tests in lab. (Jul 06)

GOCE ESA mission:
- 6 Electrostatic accelerometers for the full tensor gravity gradiometer
Tests on horizontally controlled table
A Mission concept relying on best current technologies and models

DEMETER launched in 2004

CNES micro satellite

ONERA Accelerometer
ZARM drop tower

OCA Space
Geodesy & Astrometry

ESA FEEP

Jason altimetry

MICROSCOPE
FEEP

Pos Det

ADC
Control Laws
Drag Free Control

DVA

DAC

ADC

Science Data Output
Free fall tests in ZARM

ZARM drop tower

Comparison between GRACE and GOCE inst. along vertical

$2.10^{-12}$ m/s$^2$/Hz$^{1/2}$ from 5 to 100 mHz
A family of space accelerometers

- **CHAMP - STAR**
  - $\Gamma_n : 10^{-10}$ ms$^{-2}$/Hz$^{1/2}$
  - $\Gamma_{\text{max}} : 5 \cdot 10^{-5}$ ms$^{-2}$
  - [10$^{-4}$; 10$^{-1}$]Hz
  - Two in orbit from Mar 02

- **GRACE - SuperSTAR**
  - $\Gamma_n : 3 \cdot 10^{-9}$ ms$^{-2}$/Hz$^{1/2}$
  - $\Gamma_{\text{max}} : 10^{-4}$ ms$^{-2}$
  - [2$ \cdot 10^{-4}$; 10$^{-1}$]Hz
  - One in orbit from Jul 00

- **ASTRE**
  - Microgravity sensor
  - 1 mg down to 3 nanog
  - 3 shuttle flights in 95-96

- **MICROSCOPE**
  - $\Gamma_n : < 3 \cdot 10^{-15}$ ms$^{-2}$ @ $f_{EP}$
  - $\Gamma_{\text{max}} : 3 \cdot 10^{-8}$ ms$^{-2}$
  - [10$^{-4}$; 4$ \cdot 10^{-3}$]Hz

- **GOCE - GRADIO**
  - $\Gamma_n : 2 \cdot 10^{-12}$ ms$^{-2}$/Hz$^{1/2}$
  - $\Gamma_{\text{max}} : 6 \cdot 10^{-6}$ ms$^{-2}$
  - [5$ \cdot 10^{-3}$; 10$^{-1}$]Hz
  - to be launched in 07
A Mission concept relying on best current technologies and models

- CNES micro satellite
- ONERA Accelerometer
- ZARM drop tower
- OCA Space Geodesy & Astrometry
- ESA FEEP

DEMETER launched in 2004

Jason altimetry

MICROSCOPE FEEP

ESA MICROSCOPE FEEP
A Mission concept relying on best current technologies and models

DEMETER launched in 2004

CNES micro satellite

ONERA Accelerometer

ZARM drop tower

ESA FEEP

OCA Space

Geodesy & Astrometry
MICROSCOPE Test Principle

- Earth: Gravity Source
- Two pairs of masses
  - Made of different composition in free fall
  - Test: Pt/Ti
  - Reference: Pt/Pt
- Maintained on the same orbit (<10^{-11} m)
  - by electrostatic forces
  - → Test measurement
- Low noise:
  - Long duration integration (>20 orbits) & numerous measures
  - Drag compensated satellite
  - Very clean thermal environment
- EP violation signal well defined
  - Phase: attitude wrt position in orbit
  - Frequency: $f_{\text{orb}} + f_{\text{spin}}$

<table>
<thead>
<tr>
<th>Material</th>
<th>$B/\mu$</th>
<th>$Z/\mu$</th>
<th>$(N-Z)/\mu$</th>
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<tr>
<td>Pt</td>
<td>1.008009</td>
<td>0.40296</td>
<td>0.20208</td>
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<tr>
<td>Ti</td>
<td>1.00911</td>
<td>0.46309</td>
<td>0.08273</td>
</tr>
</tbody>
</table>

Test accuracy: $\delta = 10^{-15}$
Specified per session of 1 day to 1 week
Mission duration: 1 year

$f_{ep} = f_o + f_s$
The Orbit

Pointing

- Inertial or rotating satellite:
  2 spin freq. : \((\pi +1/2) f_{\text{orb}} \) & \((\pi +3/2) f_{\text{orb}}\)
- Finely controlled requiring
  Attitude Estimator from SST & Instrument data, up to a few 0.1 µrad:
  sensitive to S/C thermal behavior

HELIOSYNCHRONOUS

- Thermal stability
- Maxi power with less solar panels
  (stiff S/C : high frequency modes)
- No eclipse during measurement phase

QUASI-CIRCULAR & POLAR

- Eccentricity < 5.10^{-3}
  To limit Earth gravity gradient (Egg) @ \(f_{EP}\)
- Known better than 5. 10^{-5}
  To correct measurements from Egg effects

Satellite altitude

- 730 or 790 km : Larger signal
  Less radiation (electronics)
  Higher \(f_{\text{orb}}\)
  (to 1400 km : No eclipse,
  Less thermal disturbance)
- Position to be known from 7 m, 14 m to 100m (for Earth gravity gradient corrections)
A satellite coming from MYRIADE line

Desorption system

SST Electronics

µDPU

PCDU

OBC

Pyro

RX/ TX2

RX/ TX1

Magnetotorquer

No gyros

With Cnes Courtesy
Electric Propulsion System: Baseline Configuration for the drag-free control

**4 Electric Propulsion Subsystem Assembly, Cluster of 3 FEEP thrusters**

Cesium FEEP

=> Specific constraints & Electrostatic Discharge risk

- **EPS total mass = 41 kg**
- **Average power ~100 W (@ 30 µN)**
- **Maximum power = 4 x 53 W = 212 W**

**Drag free system specs:** $3 \times 10^{-10} \text{ ms}^{-2} \text{Hz}^{-1/2}$ along 3 axes

$10^{-12} \text{ ms}^{-2}$ @ $f_{EP}$
## Alternate Solutions

### Indium FEEP:

**Interest:**
- low interaction with water vapor
- tested

**Drawbacks:**
- limited thrust (50 μN) ⇒ clusters
- ⇒ weight and power very high for microsatellite

### Proportional cold gas thruster:

**Interest:**
- relatively simple ⇒ reliability
- reduced power consumption 50 W (reduced solar panel area : x 0.6)

**Drawbacks:**
- small Isp ⇒ mass increase : + 20kg

*Possible back-up with double solar panels*

*AAS (Laben)*
**Instrument Description**

2 identical instruments cores, **Sensor Units (SU)** =

- 2 Electrostatic Differential Accelerometers
  
  *Each = 2 Inertial sensors with two concentric masses*

2 identical **Front End Electronics Units (FEEU)**

- **Low noise/ High stability Analog Electronics**
- **2 X 6 electrostatic channels + measurements**

2 Interface **Control Unit (ICU)** stacked

- **Digital Logics and Electronics 1 DSP + 2 FPGA**
- **Power Control Unit with very stable secondary voltages (+/-45V, +/-15V, +5V, + 3.3V)**

*Control laws, S/C data bus interfaces*
Sensor Head Technology

- SIO₂ material
- Optical grinding
- Ultrasonic machining
- Gold coating by RF diode sputtering
- Clean room integration
- High vacuum housing and magnetic shielding
- Micrometer, arc second accuracies
Challenging new technology:
- Cylindrical Shapes (mass, electrodes)
- Accuracy of mass and electrode cylinder geometries
- 2 concentric sensors & Relative positioning and centering
- Ultra-vacuum technology for connectors and gaskets
- Blocking mechanism
- Integration procedures

Sensor Unit

36 x 35 x 18 cm³
Sensor Unit Mechanical Assembly

- Test masses
- Axial electrodes
- Spinl electrodes
- Radial electrodes
- Elect. Shield
Instrument Development

Lab model: Sensor core
- 1 test-mass in silica (15g)
- Electrostatic control loop for coupling and stiffness assessment

Lab model: Electronics
- Analog sensing and control
- 300 V to 800 V for 1g levitation

2004-2008
- MR-VIB: Sensor core
  - 2 TM in W alloy

2006
- Vibration tests for design assessment
- Integration process development

Z (µm) vs. dB vs. Hz vs. t (s)
Integration procedures
- 5µm diameter gold wires, implementation.
- Silica parts, positioning and alignment.
- Blocking forces, adequate.

Vibrations
- Resonances identified at specific vibration frequencies (≈ 700 Hz)
- Blocking mechanism compatible with the updated vibration levels
- Blocking mechanism tank successfully tested with over-pressure of 100 bars
Front End Electronics Unit

**FEEU: accurate analog electronics functions**
- Test mass position sensing
- Actuations
- Reference voltages generation
- HK data measurement

**Budget:**
- Volume: 274×171×89.50 mm³
- Mass (EM): 3.045 kg
- Power: 6.4 W

6 capacitive position sensors
5×10⁻¹⁹ F/Hz¹/²

6 pairs of Drive Voltage Amplifiers
2×10⁻⁷ V/Hz¹/²

- Reference voltage sources (Vp, Vd)
- Housekeeping data
- Digital interface with ICU (FPGA, drivers)
Performance drivers (1/3)

- **S/C position tracking (Doppler)**: \(< 23\text{m}, < 23\text{m}, 100\text{m accuracy} @ fep\)

- **Attitude Control**:
  - **Pointing**: \(10^{-3}\) rad with variations \(< 24\ \mu\text{rad (inertial)} \& 0.4\ \mu\text{rad (spin)} @ fep\)
  - **Angular velocity variations**: \(< 2.5 \times 10^{-9}\ \text{rad/s (spin)} @ fep\)
  - **Angular accelerations variations**: \(< 2.3 \times 10^{-11}\ \text{rad/s}^2 \) (inertial) \& \(< 1.5 \times 10^{-11}\ \text{rad/s}^2 \) (spin) @ fep

- **Drag-Free Control**: \(< 3.10^{-10}\text{ms}^{-2}\text{Hz}^{-1/2}\ \text{noise and} < 10^{-12}\text{ms}^{-2}\ \text{variations} @ fep\)

Results from definitions and simulations presented at Cnes satellite PDR
Performance drivers (2/3)

\[ \Gamma_{app,k} \approx \frac{F_{ng}}{M_j} + \frac{M_g}{M_j} \cdot g\left(O_{sat}\right) - \frac{m_{gk}}{m_{Ik}} \cdot g\left(O_{sat}\right) + \left[I - \left[In\right]\right] \cdot \vec{O}_k \cdot \bar{O}_{sat} \]

\[ \Gamma_{app,d} = \frac{1}{2} \cdot \left(\Gamma_{app,1} - \Gamma_{app,2}\right) \]

Instrument characteristics and in-orbit calibration:

- **Resolution**: \(< 10^{-12} \text{ms}^{-2} \text{Hz}^{-1/2} \text{ and } 10^{-9} \text{rads}^{-2} \text{Hz}^{-1/2}\>
- **Stability of sensitivity**: \(< 6.8 \times 10^{-8} \text{ sine (FEEU thermal effect) and } 1.2 \times 10^{-5} \text{ Hz}^{-1/2} @ fep \>
- **SF matching**: \(< 1.5 \times 10^{-4} \>
  - **with stability**: \(< 0.3 \times 10^{-8} \text{ sine (SU thermal effect) and } 3.10^{-6} \text{ Hz}^{-1/2} @ fep \>
- **Alignment matching**: \(< 5.10^{-5} \text{ rad} \>
  - **with stability**: \(< 1.5 \times 10^{-9} \text{ rad sine (SU thermal effect) and } 3.10^{-7} \text{ rad Hz}^{-1/2} @ fep \>

*Results from instrument & satellite definitions and simulations presented during instrument & mission PDR*
Experiment Environment

**Magnetic:**
- $< 10^{-4} \text{Am}^2 \text{ variations } @ \text{ fep to 0.3 m}$
- Test-mass magnetic susceptibility:
  $$X_{P \text{ t alloy}} = 2.8 \times 10^{-4} ; \quad X_{Ti \text{ alloy}} = 7.1 \times 10^{-5}$$
- Shield from magnetic field and gradients,

  Obtained through Supranister case & INVAR SU tight housing
  (Tests realized in CNES and in ONERA lab.)

**Self-gravity:**
- Variations of the self-gravity gradient specified $< 10^{-11} \text{s}^{-2}$
- Thermo-mechanics Finite Element Models
  + Temperature fluctuations $\rightarrow$ 10 less gradients on the masses

**Thermal accommodation:**
- $1 \text{mK } @ \text{ fep on SU at the unit interface}$
- $10 \text{mK/m } @ \text{ fep on SU at the unit interface}$
- $10 \text{ mK } @ \text{ fep on FEEU at the unit interface}$
- $1 \text{ K } @ \text{ fep on ICU at the unit interface}$
Specific double insulation Payload Case for integration in the satellite

Thermal stability of SU & FEEU with passive insulation and anti-Sun radiator

CNES Thermal model being integrated before tests
From interface Temperature to relevant Temperature:
Photons/Molecules thermalized on gold coated silica surrounding masses
Temperature filtered out @ $f_{EP}$ by a factor 5

100 x 10 mK p.top. sine variation @ interface
=> 100 x 2mK p.top. sine variation on silica parts

3D finite elements
Thermal model
Temperature fluctuation Impact (SU)

Radiation pressure: \( < 3.2 \times 10^{-16} \text{ m s}^{-2} \) (worst case* @ fep)

Difference of forces exerted on each test-mass by photons pressure when temperature difference varies on each side in regards to mass \( \Delta T_{Si} \)

\[
Pr = \frac{4\sigma}{3c} T^4
\]

\[
\Gamma_n = \frac{1}{m} \left( Pr \frac{4\Delta T_{Si}}{T} \right) S
\]

Radiometer effect: \( < 2.2 \times 10^{-16} \text{ m s}^{-2} \) (worst case* @ fep)

Difference of forces exerted on each test-mass by residual gas pressure \( P_g \) when temperature difference varies on each side in regards to mass \( \Delta T_{Si} \)

\[
\Gamma_n = \frac{1}{m} \left( P_g \frac{\Delta T_{Si}}{T} \right) S
\]

Outgassing: \( < 2.5 \times 10^{-17} \text{ m s}^{-2} \) (worst case* @ fep)

Difference of forces exerted on each test-mass by variation of gas pressure \( \Delta P_g \) induced by the outgassing of the gold coated silica parts

\[
\Delta P_g \propto \frac{\Delta \text{grad}T_{Si}}{T^2}
\]

\[
\Gamma_n = \frac{1}{m} \Delta P_g S
\]

Gold Wire stiffness: thermal stability \( < 1.7 \times 10^{-15} \text{ m s}^{-2} \) (worst case @ fep)

Electrical link between mass and Voltage Reference: 5µm \( \phi \) wire when temperature varies, Young Modulus varies

\[
\Gamma_n = \frac{1}{m} k_{wire} x \left( \frac{1}{E \partial T} \right) \Delta T_{Si}
\]

Worst case*: lower density mass & inertial pointing (lower \( f_{EP} \), thus less thermal filtering)
FEEU THERMAL VACUUM TESTS

Tests performed in CNES facility with the ONERA FEEU EM

Unit Power consumption fluctuations
Spec: < 5 mW @ fep; Verified: <3 mW

Thermal Filtering focused on Vp reference voltage:
factor 2 expected

Vp area
Thermal response
Interface
(1K step variation)
Temperature Fluctuation Impact: major effects

Electrostatic stiffness & bias force:

Thermal stability $< 1.8 \times 10^{-15} + 1.10^{-15} \text{ ms}^{-2}$ (worst case @ fep)
- Bias due to geometrical dissymmetry (Cylindricity, electrode geometry,…) or to electrical dissymmetry (capacitive sensor position offset $\Delta_{\text{CSoffset}}$, …)

$$\Delta \text{Bias} \approx A_{\text{geometry}} \left[ \frac{\Delta_{\text{cylind}}}{\text{gap}} \right] \frac{\partial \left( V_p^2 + V_d^2 \right)}{\partial T} \Delta T_{\text{FEU}}$$

Scale factor stability:
- $< 6.5 \times 10^{-6} \text{ K}^{-1}$, effect depending on S/C drag compensation system performance
  - Due to $V_p$ stability (40µV/K) and to ADC reference source stability (30µV/K)
  - Interest of thermal insulation of these circuits wrt unit interface
  - Interest of regulated power line and steady power consumption

Thermal variations mainly due to Reference Voltage source:
- being improved by an expected factor 4 with up-dated components

$$\left( \frac{\partial V_p}{\partial T} \right) = 40 \mu \text{V} / \text{K}$$
Mission Performances:

Rotating satellite session: \( f_{EP} = (I + 3/2) f_{orb} \approx 8 \times 10^{-4} \text{Hz} \)

- **More than 70 error terms taken into account:**
  - Bias: 18, noise: 17, sf: 1
  - Temperature sensitivity: 30 + 3; thermal gradient sensitivity: 3
  - Magnetism: 2

**Major terms**

<table>
<thead>
<tr>
<th>Term</th>
<th>Error ( \text{ms}^{-2}/\text{Hz}^{1/2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coriolis (differential mode)</td>
<td>5.12 E-13</td>
</tr>
<tr>
<td>PM Motion (differential mode)</td>
<td>3.11 E-13</td>
</tr>
<tr>
<td>Accelerometer measurement noise</td>
<td>1.34 E-12</td>
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<tr>
<td>Bias sensitivity to thermal gradient variation</td>
<td>3.75 E-13</td>
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</table>

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<thead>
<tr>
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<tbody>
<tr>
<td>Coriolis (differential mode)</td>
<td>1.71 E-15</td>
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<tr>
<td>PM motion (differential mode)</td>
<td>1.04 E-15</td>
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<tr>
<td>PM position (differential mode)</td>
<td>8.68 E-16</td>
</tr>
<tr>
<td>Bias sensitivity to thermal gradient variation</td>
<td>1.25 E-15</td>
</tr>
</tbody>
</table>

**Budget**

Total random errors: \( B = 1.6 \times 10^{-12} \text{ms}^{-2}/\text{Hz}^{1/2} \)
Integration duration: \( T_i = 20 \text{ orbits @ } h = 730\text{km} \)
4 major tone errors: \( D = 4.9 \times 10^{-15} \text{ms}^{-2} \)
\( (D = 2.5 \times 10^{-15} \text{ms}^{-2} \) with quad. sum)

\[ \eta = \sqrt{\frac{D^2 + B^2}{T_i}} g(H) = 0.9 \times 10^{-15} \]

Value compatible with the specification: \( 1 \times 10^{-15} \) per session
At least 50 sessions during the 1 year mission
Payload & Satellite definition achieved
PDRs conclude with no mission stopping items
but 6-12 months needed more to assess FEEP or other solution,

Instrument :
SU definition can be still optimized :
for resistance to vibration : according to selected launcher requirements
for thermal stability : SU Temp. gradient can be improved
& ref. voltage source can be more thermally insulated

Error analysis to be completed with experimental results
and correlation analysis

End 2006 : Payload key point before QM production
2007 : QM production & tests
2008 : FM production & tests
2009 : FM qualification & delivery

End 2006 : Mission Performance key point
Mid 07 : Propulsion System Review
2007, 2009 : satellite development

Launch date :
2009-2010 depending on Propulsion System delivery
"So, we have decided to undertake new researches, on new basis and with original methods"

“Let me add more: this is what we have decided”

Thanks,
Questions?

Pierre.Touboul@onera.fr

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