THE MICROSCOPE MISSION: TWO YEARS BEFORE THE LAUNCH

Pierre Touboul,
on behalf of the MICROSCOPE Team

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ESA Copernicus programme’s Sentinel satellites!

- Copernicus programme: Global Monitoring for Environment (EC with ESA partnership)
- Five families of Sentinel satellites
- Sentinel-1 is a two satellites constellation with prime objectives of Land and Ocean monitoring: C-Band SAR data (accurate imaging in all weathers) following ERS-2 and Envisat.
- Sentinel 1a ready for launch in spring 2014: heliosynchronous orbit at 786 km
- Sentinel 1b to be ready for launch as soon as sept. 2015 with Soyuz (object: end of 2015)
Copernicus programme : Global Monitoring for Environment (EC with ESA partnership)

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C-Band SAR data (accurate imaging in all weathers) following ERS-2 and Envisat.

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Sentinel 1b to be ready for launch as soon as sept. 2015 with Soyouz (object: end of 2015)
Physics is not completely understood → new Physics
   → New experiments
   → New type of results

UFF violation → one of the invariance of the EEP (UFF, LPI, LLI) violated!

$$\delta_{i2} = 2 \frac{m_x^1 - m_x^2}{m_i^1 m_i^2} = \frac{m_x^1}{m_i^1} - \frac{m_x^2}{m_i^2} = 0 ?$$

MICROSCOPE Objective: $10^{-15}$ accuracy

MICROSCOPE is the first accurate UFF test in space

Scientific results + Return on Space technology limitations

- Thermal, magnetic, structural, acceleration stabilities @ picometer/s$^2$
- On board calibration with satellite control
- Accurate pointing with SST and Angular Accelerometer
- Scientific Mission Center with Mission Scenario Management
### Reference scenario

Before the launch, a reference scenario is established. It includes the following steps:

- **Commissioning step 1:** 29 days, operation of all sub-systems & payload verified.
- **Commissioning step 2:** 20 days, drag free and calibration operation validated.
- **Preliminary tests and Performance tests:** 25 + 29 days.
- **EP tests:** 92 + 52 days.
  
  \[(\text{Calibrations} + 2 \text{ spins} + 2 \text{ inertial orientations} + 2 \text{ test mass centring}) \times (\text{EP} + \text{REF})\]
- **Complementary EP tests:** 71 days.

Breaks periods with satellite in operating mode without thrusters & gas consumption are scheduled and can be added (used to take advantage of the obtained results).

### Working scenario

A working scenario is to be executed:

- **Cover 1 month**
- **Is updated every week and validated through Drag-free Expertise and Control Center**
- **Sequences mentioned as:**
  
  \[
  \begin{align*}
  \text{AE} &= \text{to be Executed} \quad (Q = \text{qualified or AQ= to be qualified}) \\
  \text{AC} &= \text{to be confirmed} \\
  \text{C} &= \text{confirmed} \\
  \text{EC} &= \text{Running} \\
  \text{E} &= \text{Executed or EI = Executed but non successful,}
  \end{align*}
  \]

- Executed scenario updates the reference scenario of the whole mission to compute the whole gas consumption and predict the offered possibilities.
UFF and MICROSCOPE space experiment...

- 2 test masses made of different composition
- Gravitational Source: the Earth
- Kinematic Acceleration: the orbital motion
- Identical initial conditions of motion

<table>
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- Permanent pico-meter control of the 2 masses
- Measurement = Necessary forces to control the same orbital motion
- No fluctuations of the mass environment due to relative motion
- Centring: 20 µm when the mass are levitated
  → Gravity Gradients corrected or centring controlled @ 0.1 µm in orbital plane (X,Z)
- Satellite imposes the common motion: reduced → instrument better operation
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Galileo Galilei

« Free fall » in space

Microscope
MICROSCOPE PROVIDED MEASUREMENTS

\[
\frac{\ddot{F}}{m_{i}^{el}} - \frac{\ddot{F}}{m_{j}^{el}} = (\delta_{j} - \delta_{i}) \bar{g}(O_{j}) + (1 + \delta_{i}) T \overrightarrow{O_{i}O_{j}} - R_{in, COR} \left( \overrightarrow{O_{i}O_{j}} \right) - \frac{\ddot{F}}{m_{i}^{pa}} + \frac{\ddot{F}}{m_{j}^{pa}}
\]

\[
\bar{g}(O_{j}) - \bar{g}(O_{i}) = [T] \overrightarrow{O_{i}O_{j}} + O(T^2)
\]

- centering
- shape: spherical inertia, multipoles
- material density homogeneity

- Angular acceleration & centrifugal acceleration: to be controlled
- Coriolis & Cinematic relative acceleration
  ⇒ stability of the ULE configuration and electrostatic servo-control

2 years mission duration: fine survey of gas consumption
Heliosynchronous orbit ~ 710 km → 1.7 × 10^-4 Hz
Passive temperature stabilities

Compensation of the drag by GAIA type thrusters
Attitude control without gyro. and wheels
Inertial and rotating pointing → 1 mHz

No moving masses and structural motions @ f_{EP}
Position and attitude sufficiently well known

Payload contributes to s/c motion control
S/C contributes to Payload outputs
MICROSCOPE Satellite: a space lab.

2 differential electrostatic accelerometers in thermal cocoon
MICROSCOPE Satellite: a space lab.

2 differential electrostatic accelerometers in thermal cocoon

Magnetic cocoon

Payload at the center of the satellite:
- for thermal stability
- for spin mode
- for self gravity
MICROSCOPE Satellite: a space lab.

- 2 differential electrostatic accelerometers in thermal cocoon
- Magnetic cocoon
- Payload at the center of the satellite:
  - for thermal stability
  - for spin mode
  - for self gravity
- Payload and star sensor for attitude & orbit control
  And for calibration
MICROSCOPE Satellite: a space lab.

2 differential electrostatic accelerometers in thermal cocoon

magnetic cocoon

payload at the center of the satellite:
- for thermal stability
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payload and star sensor for attitude & orbit control
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MICROSCOPE Space Lab. with 6 DoF Controlled to the benefit of the environment stability

Earth Gravity Gradient $\Rightarrow$ eccentricity $< 5 \times 10^{-3}$
S/C position tracking (Doppler): $< 7m, < 14m, 100m \text{ @ fep}$
Pointing: $10^{-3}$ rad with variations $< 10 \mu\text{rad (inertial)}$ & $10 \mu\text{rad (spin)} \text{ @ fep}$

Mass Off-Centering $\Rightarrow$ Angular velocity variations $< 10^{-9} \text{ rad/s (spin)} \text{ @ fep}$
Angular accelerations variations $< 10^{-11} \text{ rad/s}^2 \text{ (inertial)}$ & $5.10^{-12} \text{ rad/s}^2 \text{ (spin)} \text{ @ fep}$

Sensitivity Matching $\Rightarrow$ Drag-Free Control $< 3.10^{-10} \text{ ms}^2\text{Hz}^{1/2}$ and $< 10^{-12} \text{ ms}^2 \text{ @ fep}$
Space Electrostatic accelerometers for Earth gravity field recovery

- **GRACE (NASA-JPL), March 2002 – 2015**
  - altitude ~500km
  - $\Gamma_n: 1.0 \times 10^{-10} \text{ms}^{-2}/\text{Hz}^{1/2}$
  - $\Gamma_{\text{max}}: 510^5 \text{ms}^{-2}$
  - $[0.1 \times 10^{-3}; 10^{-1}] \text{Hz}$

Today: 3971 days in orbit

- **GOCE (ESA), March 2009 – October 2013**
  - altitude ~260km
  - $\Gamma_n: 2.0 \times 10^{-12} \text{ms}^{-2}/\text{Hz}^{1/2}$
  - $\Gamma_{\text{max}}: 610^6 \text{ms}^{-2}$
  - $[5 \times 10^{-3}; 10^{-1}] \text{Hz}$

Courtesy TAS-F
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- [5 \times 10^{-8}; 10^{-1}] \text{ Hz}

Accelerometer PSD in 40-100 mHz
- \( \text{ASH}_{3,6}: 6.7 \times 10^{-12} \text{ m/s}^2/\text{Hz}^{1/2} \)
- \( \text{ASH}_{1,4}: 3.9 \times 10^{-12} \text{ m/s}^2/\text{Hz}^{1/2} \)
- \( \text{ASH}_{2,5}: 3.1 \times 10^{-12} \text{ m/s}^2/\text{Hz}^{1/2} \)

GOCE
- Gold wire: \( \varnothing=5 \mu m \)
- PT-Rh Proof mass: \( m=320 g \)
- Gap Y,Z: \( e=299 \mu m \)
- PM Polarisation: \( V_p=7.5 \text{ V} \)
- Detection: \( V_d=7.6 \text{ V @ 100 KHz} \)
- Detector gain: \( 1.7 \text{ mV / nano-m} \)
- Scale factor:
  - Science data: \( 1.10^{-3} \text{ms}^3/\text{V} \)
  - DFACS data: \( 17.10^4 \text{ ms}^3/\text{V} \)
  - Range: \( \pm 6.5 \times 10^{-8} \text{ ms}^2 \)
  - Expected Res. < \( 2 \times 10^{-12} \text{ ms}^2/\text{Hz}^{1/2} \)

MicroSCOPE
- Gold wire: \( \varnothing=7.5 \mu m \)
- m=1400 - 307 g
- \( e=600 \mu m \)
- \( V_p=5 \text{ V} \)
- \( V_d=7.07 \text{ V @ 100 KHz} \)
- Detector gain: \( 0.3 - 0.26 \text{ mV / nano-m} \)
- Scale factor:
  - Science data: \( 1.8 - 2.1 \times 10^{-7} \text{ ms}^3/\text{V} \)
  - DFACS data: \( 0.7 - 1.7 \times 10^{-4} \text{ ms}^3/\text{V} \)
  - Range: \( \pm 4.8 - 4.6 \times 10^{-8} \text{ ms}^2 \)
  - Expected Res. < \( 2 \times 10^{-12} \text{ ms}^2/\text{Hz}^{1/2} \)
MICROSCOPE: A dedicated instrument

- 6 servo-channels and associated electrode sets
- Sensing and actuations
- Very steady and accurate configuration
- Cylindrical configuration
- Concentric masses
- Overlapping electrodes along X → Linearity

One differential accelerometer = 2 inertial sensors
Each inertial sensors exploits:
Electrostatic concept & Technology similar to GOCE
Instrument Design

2 Sensor Units mounted on reference plate
(2 concentric Test-Masses Pt-Rh / Pt-Rh or Ti / Pt-Rh)

SU’sQM

36 cm x 34.8 cm x 18 cm - 25 kg

MQV

2 x { 28 cm x 17 cm x 9 cm - 3.5 kg - 7 W }

MQV1 MV2

Test-Masses

Silica cylinders for electrodes set

Vacuum system

Circuit boards for coax. connections

Hermetic connectors

Base plate assembly for high accurate positioning

Blocking system

24 bars chamber

Electro-valves

Test-Masses

Silica cylinders for electrodes set
**Instrument Design**

2 Sensor Units mounted on reference plate
(2 concentric Test-Masses Pt-Rh / Pt-Rh or Ti / Pt-Rh)

30 cm x 25 cm x 11 cm – 5.5kg – 2 x 11W

36 cm x 34.8 cm x 18 cm -25kg

2 Sensor Units mounted on reference plate
(2 concentric Test-Masses Pt-Rh / Pt-Rh or Ti / Pt-Rh)

30 cm x 25 cm x 11 cm – 5.5kg – 2 x 11W

MU'sQM

Front End Electronics Unit (FEEU)
One for two masses, Low noise analog electronics with high stability:
Reference voltages
+ 2 times 6 electrostatic channels (analog part +ADC +DAC)
+ 2 times read out circuits
Instrument Design

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Interface Control Unit (ICU)
2 stacked ICU (1 per FEEU), including each:
1 DSP + 1 FPGA for test-mass control and data conditioning/interfaces,
2 Power Control Units (1 nominal + 1 redundant): very stable secondary voltages (+/-48V, +/-15V, +5V, +3.3V)
INTEGRATION FM 2 : Platinum / Titanium (1/4)
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Reference plate with silica top hat and fingers
INTEGRATION FM 2 : Platinum / Titanium (1/4)

Reference plate with silica top hat and fingers
INTEGRATION FM 2 : Platinum / Titanium (1/4)

Reference plate with silica top hat and fingers
INTEGRATION FM 2 : Platinum / Titanium (2/4)
The two masses are integrated inside their electrode rods;
Geometric control have been performed
Electrical board with connectors and getter pumping element to be mounted
INTEGRATION FM 2 : Platinum / Titanium (3/4)
INTEGRATION FM 2: Platinum / Titanium (4/4)
The 3 FEEU FM, successfully tested in performance:

- noise + bias + linearity + bandwidth + thermal sensitivity
- Interface with FM ICUs

Now, under potting after increase of the read-out range, Qualification under vibrations and thermal cycles are scheduled in Dec. 2013.
1 DSP board per differential accelerometer (No redundancy):
1 DSP $\rightarrow$ 1 SU $\rightarrow$ 12 servo-loops channels
1 DSP = 1 Oslink customer

Architecture on TSC21020F:
• Rad-tolerant FPGA
• SEL immune SRAM (SEU protected by EDAC)
• PROM containing the master (Boot) software (IMSW)
• EEPROM containing the application software (ASW) and the parameter tables.

Software and Hardware tested, accuracy verified.

• DSP hardware now compliant (more robust chronogram):
  ➢ With the whole range of operating temperature
  ➢ And with the 2 years duration of the mission
• Tests have been successfully performed
• Software 2.6 to be delivered at end of November.
Instrument status and performance verification

- **Sensors:**
  Qualification, now performed with demonstration of resistance to launch vibrations, chocks, aging (gold wire); FM 2, integrated and under tests; FM 1, integration running;
  To be delivered in March 2014

- **Analog electronics:**
  FM Tested and being potted after full range adjustment;
  To be delivered in Feb. 2014

- **Digital electronics:**
  Robustness to increase of temperature now insured;
  Software to be up-dated;
  To be delivered in Feb. 2014

- **Documentation:**
  In progress

- **Error budget**
  Now performed with QM actual values and satellite expected environment
  Spin mode : $1.12 \times 10^{-15}$ over 20 orbits and $0.66 \times 10^{-15}$ over 120 orbits
  Inertial mode : $1.42 \times 10^{-15}$ over 120 orbits
  Both limited by the sensor noise, the SU gradients of temperature variations, the SU and FEEU temperature variations.
Instrument status and performance verification

Performance test session: 29 days

- Verification of acceleration output linearity
- Sensibility of output linearity to static TM position (along the 3 axes)
- Variation of the electrostatic configuration
  - through test mass DC potential
  - observation of bias and noise
  - through test-mass sine motion: change of geometry
  - through S/C sine motion: change of electrode voltages
- Evaluation of couplings and TM self gravity
- Evaluation of Magnetic sensitivity through magneto-torque actuations
- Evaluation of thermal sensitivity of SU and FEEU with dedicated thermistances

Calibration: 3 phases of 14 days

- Before and after
- EP and REF

Error budget

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CALIBRATION: 2 servo-loops to generate well known acceleration outputs

- Drag compensation loop → To excite the linear satellite motion
  → Common excitation → Differential outputs vs drag-free point
- Attitude S/C control through SST and angular accelerometer
  → To oscillate the S/C → Differential outputs vs eccentricity or instrument attitude vs SST
- Proof-mass oscillation → Elect. Conf. modif. Or Coriolis effects
Operational & scientific organization

3 levels

- permanent activity for data processing
- monthly meetings
- weekly potential request for mission scenario & operation
- biannual meetings or quarterly for data processing organization and validation
- monthly potential requests for mission scenario

The MICROSCOPE Science Working Group promotes the exploitation of the data & is responsible in particular for:
- Supervising and approving the evaluation and the validation of the performance
- Approving the final scientific data products to be distributed to the community,
- Promoting the exploitation of the data and the diffusion of the information (colloquia...).
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Supervising and approving the evaluation and the validation of the performance

3 levels

Members of the SWG:
- The PI (ONERA) and the co-PI (OCA), Pierre Touboul, Gilles Mètris,
- The ZARM co-I for Space Physics and the DLR co-I, Claus Lämmerzhal, Hans Dittus,
- Five representatives of the already envisaged scientific themes, i.e.:
  - General Relativity and Gravitation, Thibault Damour,
  - Fundamental Interactions, Pierre Fayet,
  - Interdisciplinary Physics, Serge Reynaud,
  - Earth gravity field, Isabelle Planet,
  - Aeronomy, Peter Visser,
- One representative of similar space missions, Tim Sumner,

Guests: the CNES Fundamental Physics coordinator, Project manager, CECT chairman, Sylvie Léon-Hirtz, Michel Bach, Alain Robert and the CMS manager, Manuel Rodrigues.

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Thanks to MICROSCOPE present partners

Calibrated centring
Non Calibrated
1E-15 EP signal @ 730km

Different Acceleration (m/s²)

Calibrated centring
Non Calibrated
1E-15 EP signal @ 730km

Different Acceleration (m/s²)
THANK YOU FOR YOUR ATTENTION

QUESTIONS ?