Software tools for the validation of the in-flight calibration performance of the MICROSCOPE space mission

E. Hardy, A. Levy, M. Rodrigues, P. Touboul (ONERA), G. Métris (OCA)

SF2A 2013 (07/06/2013)

ONERA
THE FRENCH AEROSPACE LAB

retour sur innovation

The Equivalence Principle

<u>General Relativity</u>

PE → **Universality of free fall** : all bodies, independently of their mass or intrinsic composition, acquire the **same acceleration** in the same uniform gravity field

$$\frac{M_G}{M_I} = 1$$

Impossible to merge the gravitation with the three other fundamental interactions

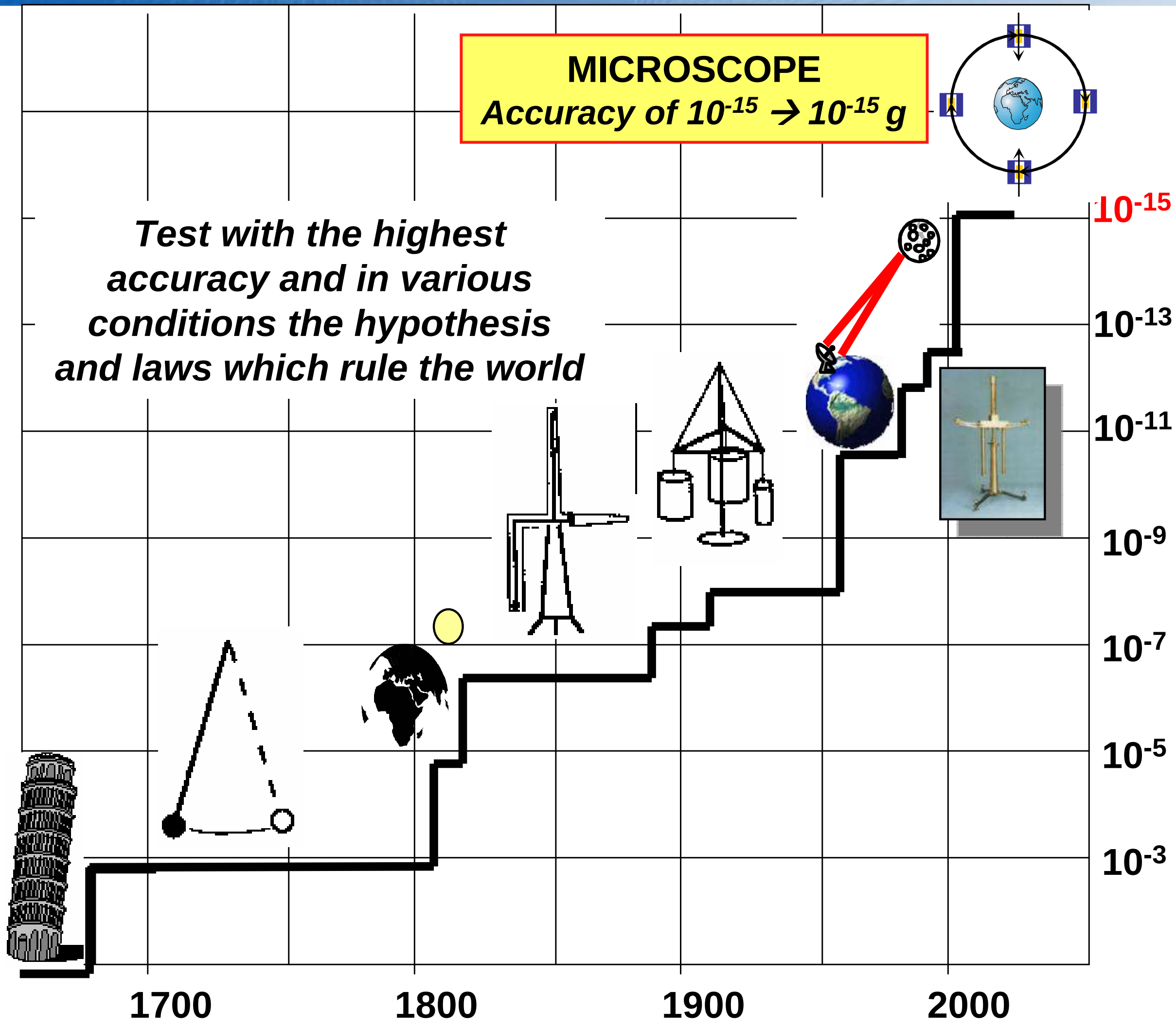
<u>Alternative theories</u>

Possible unification

⇒ New interaction?

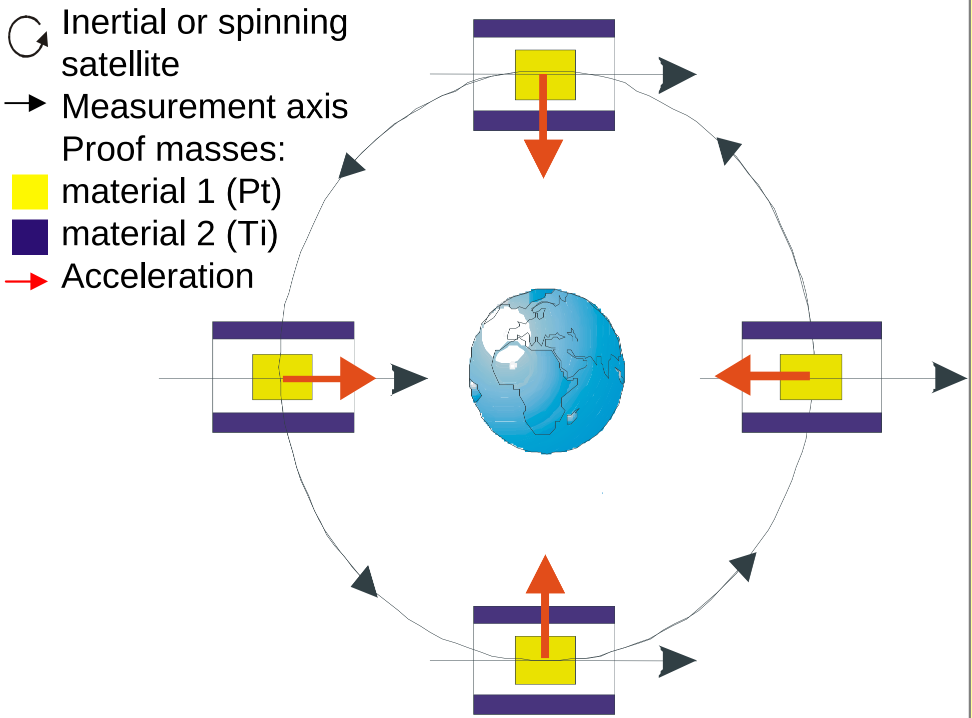
⇒Violation of the Equivalence principle?

$$\frac{M_G}{M_I} = 1+\omega$$



MICROSCOPE space experiment: test of the Equivalence Principle with an accuracy of 10^{-15}

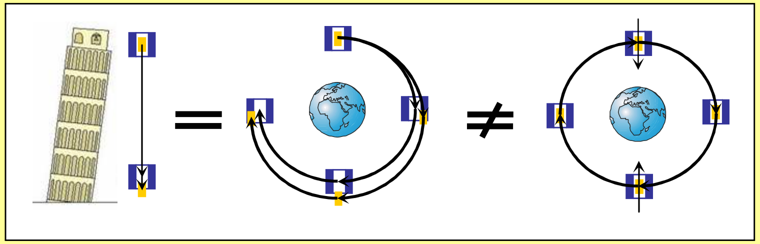
The principle of the MICROSCOPE space mission



Gravitational source: **the Earth**

inertial acceleration: orbital motion

2 masses of **different composition**: controlled **on the same orbit** (< 10^{-11}m) thanks to the measured electrostatic forces



time span of the measurement: **non limited by the free fall** (> 20 orbits)

Environment: Very controlled or avoiding perturbations, **drag-free satellite**

Signal to be detected: phases & frequency are defined $\mathbf{f_{ep}}$ =

- Inertial mode: $\mathbf{f_{orb}}$ = 1/orbit

- Spinning mode: $\mathbf{f_{orb} + f_{spin}}$

CNES MYRIADE Microsatellite

- Circular Orbit: 720 km, e < 5.10^{-3}
- Inertial or Rotating: 7.10^{-3} rd/s
- Mission duration: 12 months
- Mass of microsat: 200 kg
- Payload budgets: 35 kg, 40 Watts
- 2 differential electrostatic accelerometers

  (2 pairs of masses: Pt/Pt & Pt/Ti)

The measurement

Measurement of the accelerations applied to the test masses to keep them centered and concentric	
d: differential mode (half différence) → contains the EP violation term	c: common mode (half sum) → command of the drag-free system

EP violation parameter : $\delta = \frac{m_{2g}}{m_{2I}} - \frac{m_{1g}}{m_{1I}}$

Gravity gradient

Inertia gradient

$$\Gamma_{mes,dx} = \frac{1}{2}(\Gamma_{mes,1} - \Gamma_{mes,2}) = \frac{1}{2} K_{1cx} \cdot \delta \cdot g_{x/sat} + \frac{1}{2} \begin{bmatrix} K_{1cx} \\ \eta_{cz} + \theta_{cz} \\ \eta_{cy} - \theta_{cy} \end{bmatrix}^t \cdot [T - In] \cdot \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix}$$

$$+ \begin{bmatrix} K_{1dx} \\ \eta_{dz} + \theta_{dz} \\ \eta_{dy} - \theta_{dy} \end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + C_x) + 2 \cdot K_{2cxx} \cdot (\Gamma_{app,dx} + b_{1dx}) \cdot (\Gamma_{res_{df},x} + C_x - b_{0cx})$$

$$+ K_{2dxx} \cdot \left((\Gamma_{res_{df},x} + C_x - b_{0cx})^2 + (\Gamma_{app,dx} + b_{1dx})^2 \right)$$

b_0 : bias
b_1 : parasitic forces
$\Gamma_{res,df}$: drag-free residual
C : drag-free command

Δ : décentrage K_1 : facteur d'échelle η : couplage	θ : mésalignement K_2 : terme quadratique

ONERA THE FRENCH AEROSPACE LAB

Budget before calibration

	Signal element	Parameter concerned	Contribution before calibration ($m\cdot s^{-2}$)
Defects between the instrument and the satellite	$K_{1cx}\cdot T_{xx}\cdot\Delta_x$	$K_{1cx}\cdot\Delta_x$ < 20.2 µm	8.4×10^{-14}
	$K_{1cx}\cdot T_{xz}\cdot\Delta_z$	$K_{1cx}\cdot\Delta_z$ < 20.2 µm	8.6×10^{-14}
	$K_{1cx}\cdot T_{xy}\cdot\Delta_y$	$K_{1cx}\cdot\Delta y$ < 20.2 µm	6×10^{-16}
	$(\eta_{cz}+\theta_{cz})\cdot T_{yy}\cdot\Delta_y$	$\eta_{cz}+\theta_{cz}$ $<2.6\times10^{-3}$ rad Δ_y < 20 µm	8.6×10^{-16}
	$(\eta_{cy}-\theta_{cy})\cdot T_{zz}\cdot\Delta_z$	$\eta_{cy}-\theta_{cy}$ $<2.6\times10^{-3}$ rad Δ_z < 20 µm	6.4×10^{-16}
Defects between the two sensors	$2\cdot K_{1dx}\cdot\Gamma_{res_{df},x}$	K_{1dx} $<10^{-2}$	2×10^{-14}
	$2\cdot(\eta_{dz}+\theta_{dz})\cdot\Gamma_{res_{df},y}$	$\eta_{dz}+\theta_{dz}$ $<1.6\times10^{-3}$ rad	3.0×10^{-15}
	$2\cdot(\eta_{dy}-\theta_{dy})\cdot\Gamma_{res_{df},z}$	$\eta_{dy}-\theta_{dy}$ $<1.6\times10^{-3}$ rad	3.0×10^{-15}
Quadratic non linearities	$4\cdot K_{2,cxx}\cdot\Gamma_{app,dx}\cdot\Gamma_{res_{df},x}$	K_{2cxx} < 20000 s^2/m	8.0×10^{-16}
	$2\cdot K_{2,dxx}\cdot(\Gamma^2_{res_{df},x}+\Gamma^2_{app,dx})$	K_{2dxx} < 20000 s^2/m	8.0×10^{-16}
	Total = $\sum\lvert\ \rvert$		2×10^{-13}

Total contribution : 2.10^{-13} $m.s^{-2}$ > 8.10^{-15} (mission accuracy objective)

→ an in-orbit calibration is necessary

Calibration procedures : off-centrings

$$\Gamma_{mes,dx} = \frac{1}{2}(\Gamma_{mes,1} - \Gamma_{mes,2}) = \frac{1}{2}K_{1cx} \cdot \delta \cdot g_{x/sat} + \frac{1}{2}\begin{bmatrix} K_{1cx} \\ \eta_{cz} + \theta_{cz} \\ \eta_{cy} - \theta_{cy} \end{bmatrix}^t \cdot [T - In] \cdot \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix}$$

$$+ \begin{bmatrix} K_{1dx} \\ \eta_{dz} + \theta_{dz} \\ \eta_{dy} - \theta_{dy} \end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + C_x) + 2 \cdot K_{2cxx} \cdot (\Gamma_{app,dx} + b_{1dx}) \cdot (\Gamma_{res_{df},x} + C_x - b_{0cx})$$

$$+ K_{2dxx} \cdot \left((\Gamma_{res_{df},x} + C_x - b_{0cx})^2 + (\Gamma_{app,dx} + b_{1dx})^2 \right)$$

$K_{1cx}\Delta_x$ and **$K_{1cx}\Delta_z$**: use the important value of T_{xx} and T_{xz} at $2f_{orb}$

cosine part: $$\Gamma_{mes,dx/\cos}(2f_{orb}) = \frac{1}{2}K_{1cx} \cdot T_{xx}(2f_{orb}) \cdot \Delta_x$$

sine part: $$\Gamma_{mes,dx/\sin}(2f_{orb}) = \frac{1}{2}K_{1cx} \cdot T_{xz}(2f_{orb}) \cdot \Delta_z$$

$K_{1cx}\Delta_y$: T_{xy} too weak → oscillate the satellite around Y_{sat}

$$\Gamma_{mes,dx/\cos}(f_{cal/ang}) = \frac{1}{2}K_{1cx} \cdot (T_{xy}(f_{cal/ang}) - \alpha_0 \omega^2_{cal/ang}) \cdot \Delta_y$$

Other calibration procedures

$$\Gamma_{mes,dx} = \frac{1}{2}(\Gamma_{mes,1} - \Gamma_{mes,2}) = \frac{1}{2}K_{1cx}\cdot\delta\cdot g_{x/sat} + \frac{1}{2}\begin{bmatrix} K_{1cx} \\ \eta_{cz}+\theta_{cz} \\ \eta_{cy}-\theta_{cy}\end{bmatrix}^t \cdot [T - In]\cdot\begin{bmatrix}\Delta_x \\ \Delta_y \\ \Delta_z\end{bmatrix}$$

$$+ \begin{bmatrix} K_{1dx} \\ \eta_{dz}+\theta_{dz} \\ \eta_{dy}-\theta_{dy}\end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + C_x) + 2\cdot K_{2cxx}\cdot(\Gamma_{app,dx} + b_{1dx})\cdot(\Gamma_{res_{df},x} + C_x - b_{0cx})$$

$$+ K_{2dxx}\cdot\left((\Gamma_{res_{df},x} + C_x - b_{0cx})^2 + (\Gamma_{app,dx} + b_{1dx})^2\right)$$

1. **Parameters of the common sensitivity matrix ($\eta_{cz} + \theta_{cz}$, $\eta_{cy} - \theta_{cy}$):** oscillation of the test masses along Y and Z at f_{TM}+ modulation of the Eart gravity gradient at $2f_{orb}$ → calibration signal at $f_{TM} + 2f_{orb}$
2. **Parameters of the differential sensitivity matrix (K_{1dx}, $\eta_{dz} + \theta_{dz}$, $\eta_{dy} - \theta_{dy}$):** oscillation of the satellite along X, Y or Z through the drag-free command C
3. **Differential quadratic factor K_{2dxx}:** oscillation of the satellite along X through the drag-free command C → calibration signal at $2f_{cal/lin}$
4. **Common quadratic factor K_{2cxx}:**
   - K21xx: oscillation of the test mass 1 along X, drag-free locked on the sensor 2 → calibration signal at $2f_{TM}$
   - K22xx: oscillation of the test mass 2 along X, drag-free locked on the sensor 1 → calibration signal at $2f_{TM}$

Evaluated calibration budget

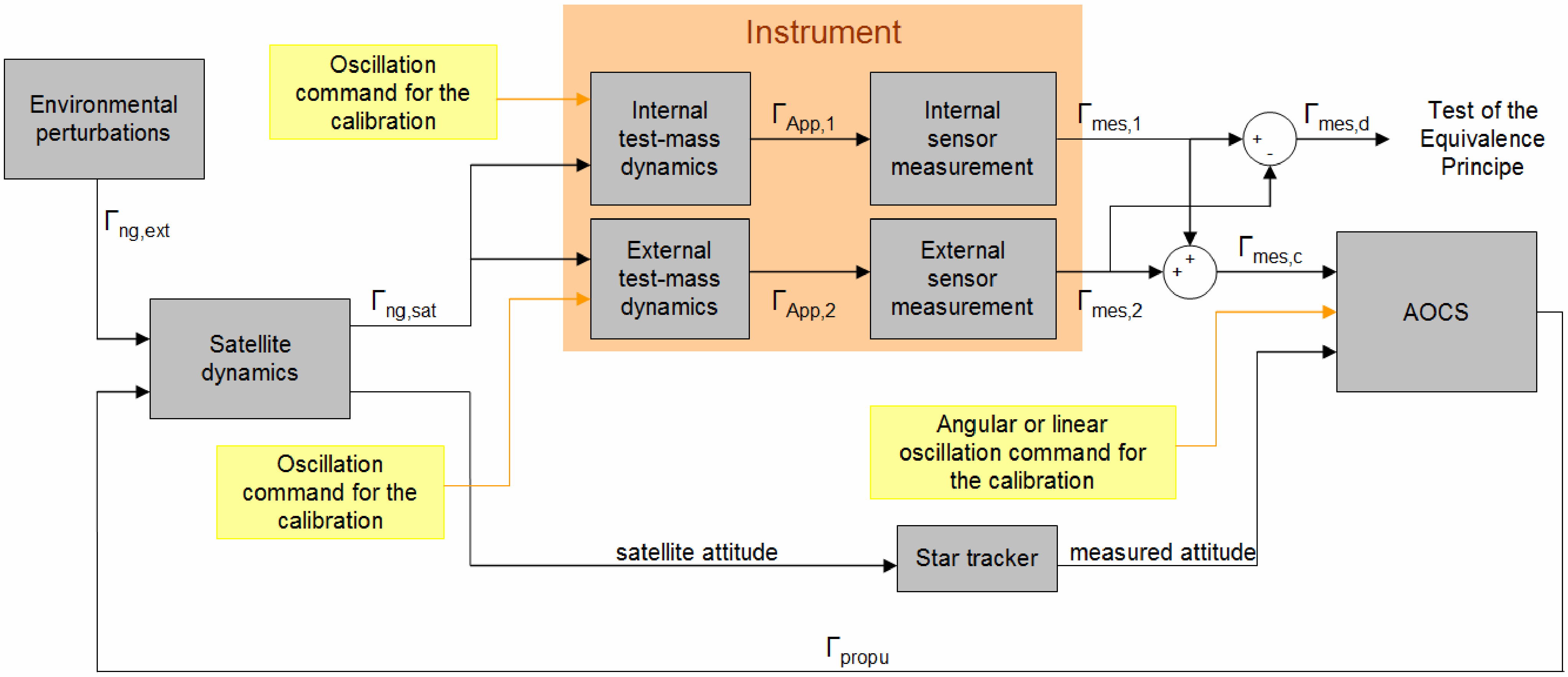
T_{cal} = 10 orbits

Parameter to be calibrated	Perfo. after calibration	Specification
$K_{1cx} \cdot \Delta_x$	0.10 µm	0.1 µm
$K_{1cx} \cdot \Delta_z$	0.11 µm	0.1 µm
$K_{1cx} \cdot \Delta_y$	1.2 µm	2 µm
$(\eta_{cz} + \theta_{cz})$	1.0×10^{-3} rad	9.0×10^{-4} rad
$(\eta_{cy} - \theta_{cy})$	9.5×10^{-4} rad	9.0×10^{-4} rad
$(K_{1dx}/K_{1cx})'$	3.1×10^{-5}	$1.5\cdot10^{-4}$
Θ_{dz}	2.3×10^{-6} rad	$5\cdot10^{-5}$ rad
Θ_{dy}	2.3×10^{-6} rad	$5\cdot10^{-5}$ rad
K_{2dxx}/K_{1cx}^2	50.2 s²/m	250 s²/m
K_{2cxx}/K_{1cx}^2	581.9 s²/m	1000 s²/m

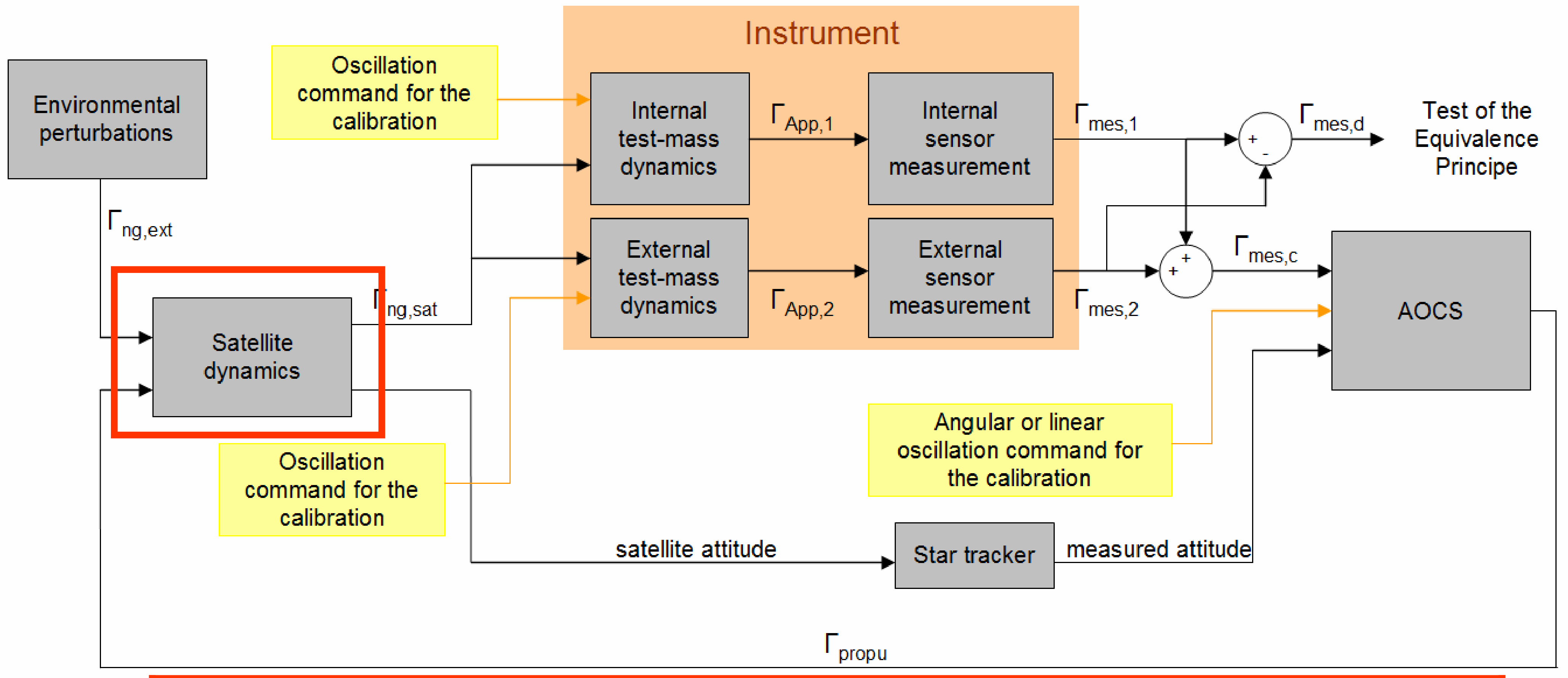
→ Simulator to test the validity of the planned calibration procedures

ONERA THE FRENCH AEROSPACE LAB

Simulateur d'étalonnage : structure

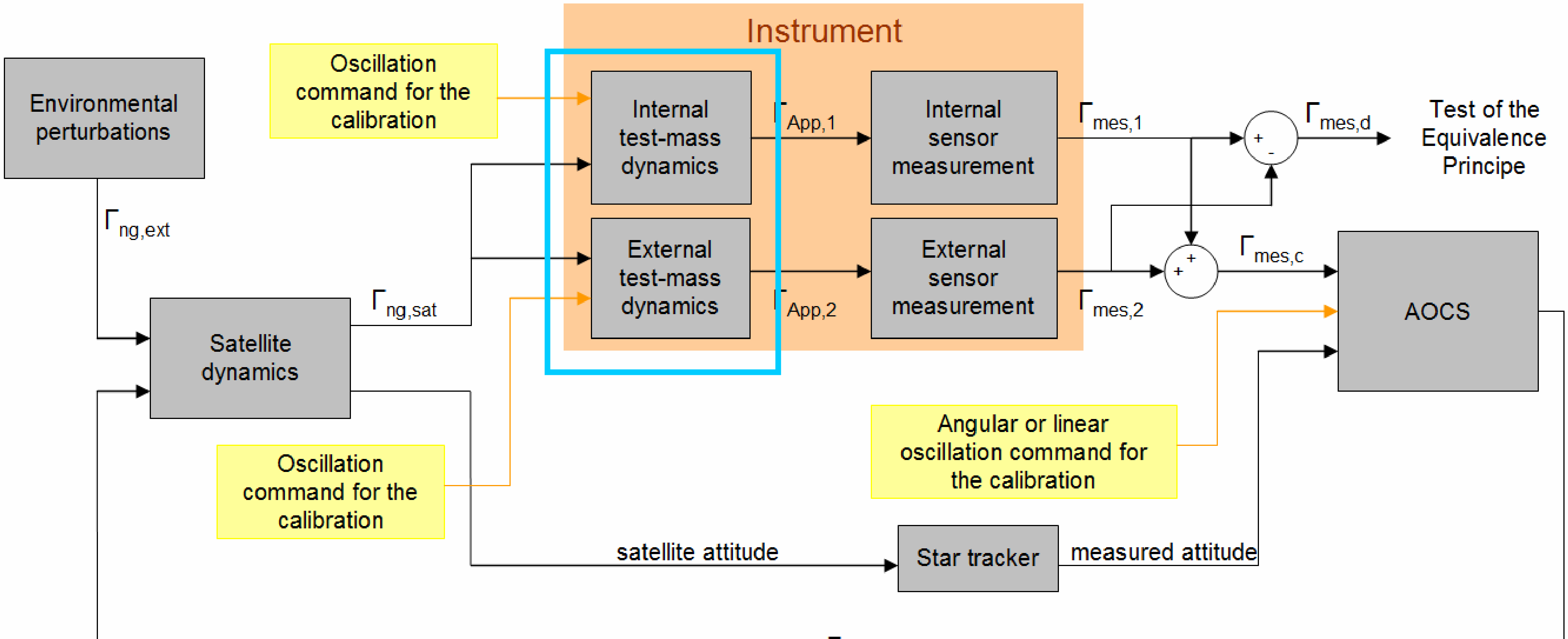


Dynamique du satellite dans un environnement perturbé



Satellite dynamics	
Input	Output
Thrust accélérration Γ_{propu}	- Non-gravitationnal acceleration of the satellite $\Gamma_{ng,sat}$ - Attitude of the satellite for the star tracker
Influence of the environmental perturbations – solar radiation pressure – residual atmospheric drag $\Gamma_{ng,sat} = \Gamma_{propu} + \Gamma_{ext,sat}$	

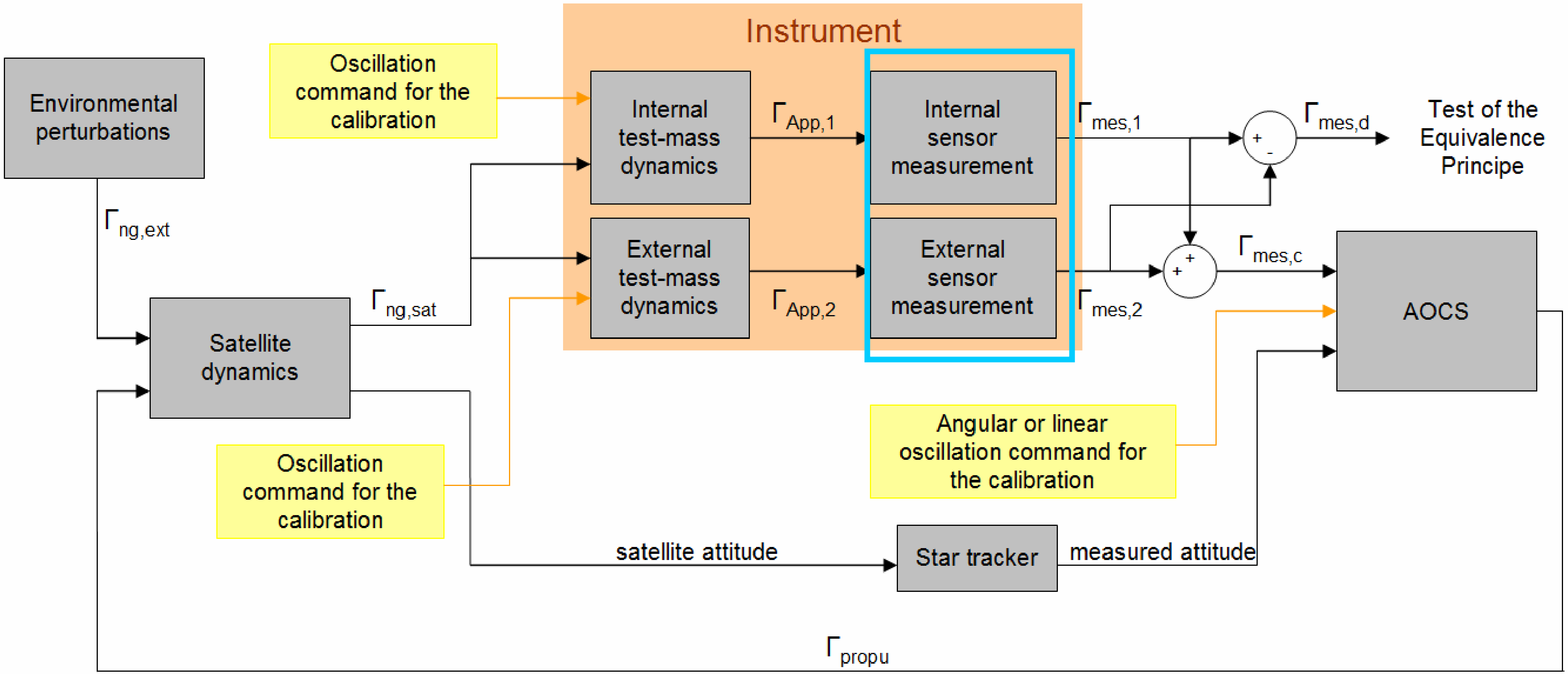
The instrument



Simulation of the electrostatic acceleration applied to test-mass k	
Input	Output
- Non gravitationnal acceleration of the satellite $\Gamma_{ng,sat}$ - Position of the test-mass relatively to the center of the electrostatic cage O_cO_k	Electrostatic acceleration applied to the test-mass k in order to keep it centered

$$\overrightarrow{\Gamma App,k} = \frac{\vec{F}_{NGsat}}{M_{Isat}} + ([T]-[In]).\overrightarrow{O_k O_c} - [Cor]\dot{\overrightarrow{O_k O_c}} - \ddot{\overrightarrow{O_k O_c}}$$

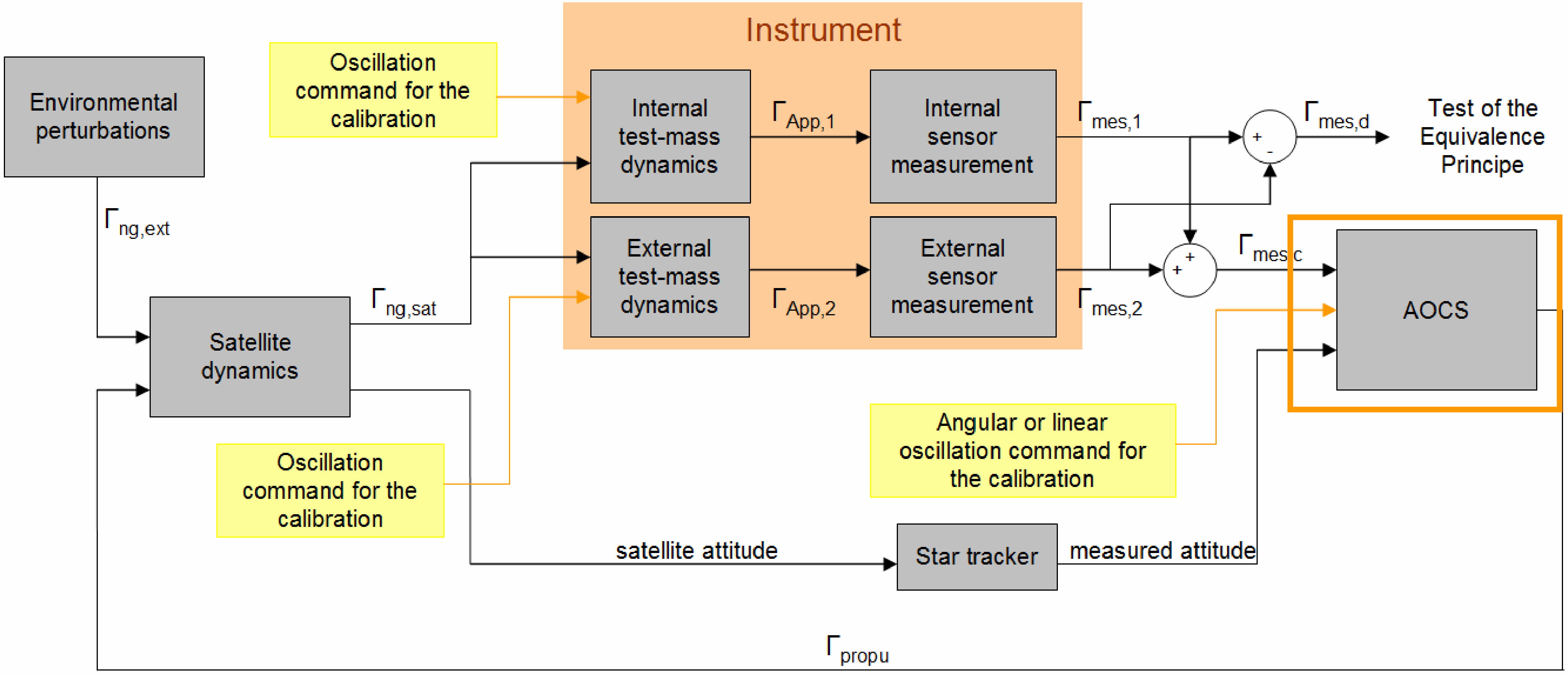
The instrument



Measurement of the applied acceleration	
Input	Output
Electrostatic acceleration applied to test-mass k to keep it centered $\Gamma_{App,k}$	Measured acceleration $\Gamma_{mes,k}$
- Bias - Noise - Sensitivity matrix : scale factor, coupling, misalignement - Quadratic factors	

ONERA THE FRENCH AEROSPACE LAB

Attitude and Orbit Control System (AOCS)



Drag-free system	
Input	Output
Common mode acceleration measurement of the test-masses $\Gamma_{mes,c}$	Acceleration applied to the satellite by the thrusters Γ_{propu}

– Hybridation of the attitude measured with the star tracker (LF) and the angular acceleration measured with the instrument (HF)

– AOCS calculator: fonction de transfert : $\Gamma_{DF} = TF_{DF} (\Gamma_{mes,c} + C_{étalonnage})$

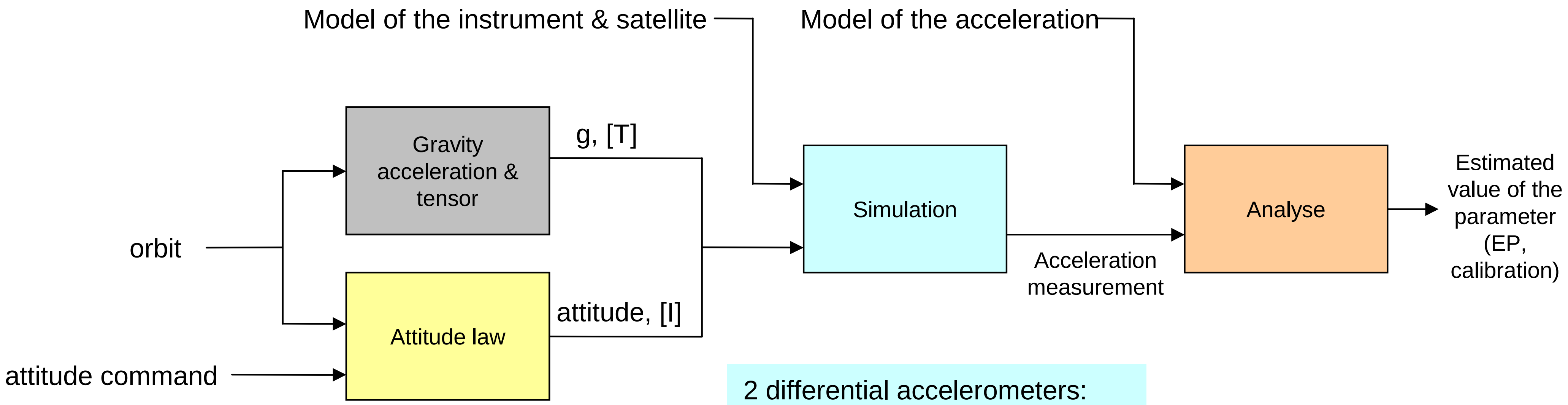
– Thrusters: sensitivity matrix and noise $\Gamma_{propu} = -[M_{propu}] \Gamma_{DF} + \Gamma_{n,DF}$

Results of the simulation

Parameter to be calibrated	Max value	Estimation accuracy: specification	Estimation accuracy: worst result	Estimation accuracy: mean result	Estimation accuracy: standard deviation
$K_{1dx}\Delta_x$	20 µm	0.1 µm	0.04 µm	0.01 µm	7.3 nm
$K_{1dx}\Delta_z$	20 µm	0.1 µm	0.05 µm	0.03 µm	6.5 nm
$K_{1dx}\Delta_y$	20 µm	2 µm	0.2 µm	0.05 µm	0.04 µm
$\eta_{cy} - \theta_{cy}$	$2.6 \cdot 10^{-3}$ rad	$9.0 \cdot 10^{-4}$ rad	$1.0 \cdot 10^{-3}$ rad	$3.1 \cdot 10^{-4}$ rad	$2.3 \cdot 10^{-4}$ rad
$\eta_{cz} + \theta_{cz}$	$2.6 \cdot 10^{-3}$ rad	$9.0 \cdot 10^{-4}$ rad	$1.1 \cdot 10^{-3}$ rad	$2.6 \cdot 10^{-4}$ rad	$2.6 \cdot 10^{-4}$ rad
$(K_{1dx}/K_{1cx})'$	10^{-2}	$1.5 \cdot 10^{-4}$	$5 \cdot 10^{-6}$	$1.6 \cdot 10^{-6}$	$1.2 \cdot 10^{-6}$
Θ_{dy}	$1.6 \cdot 10^{-4}$ rad	$5 \cdot 10^{-5}$ rad	$2 \cdot 10^{-5}$ rad	$1.0 \cdot 10^{-6}$ rad	$8.3 \cdot 10^{-7}$ rad
Θ_{dz}	$1.6 \cdot 10^{-4}$ rad	$5 \cdot 10^{-5}$ rad	$4 \cdot 10^{-6}$ rad	$1.2 \cdot 10^{-6}$ rad	$1.7 \cdot 10^{-6}$ rad
K_{2dxx}/K_{1cx}^2	14000 s²/m	250 s²/m	124 s²/m	25 s²/m	23 s²/m
K_{2cxx}/K_{1cx}^2	14000 s²/m	1000 s²/m	274 s²/m	62 s²/m	54 s²/m

Estimation accuracy after calibration : statistical analysis with 100 simulations
Session duration: 10 orbits, except for $\eta_{cz} + \theta_{cz}$: 40 orbits

Mission simulator



Attitude mode:
- inertial : X, Z in the orbital plan
- spinning: rotation around Y
- angular oscillation of the satellite

2 differential accelerometers:
- instrument parameters
- EP violation parameter
- command for the test-masses oscillation

Drag-free system:
- command for the satellite linear oscillation
- drag-free residue, noise

- measurement correction
- least squares inversion
- missing data

Calibration sessions
+ session for the EP test

→ Correction of the effects of the instrumental parameters

→ Estimation of the EP parameter with 10^{-15} accuracy

Conclusion

Calibration process definition

- The budget of the measurement equation before calibration does not comply with the objective of the EP test accuracy
- Several in flight calibrations are necessary during the space experiment
- Parameters to be calibrated have been identified and appropriate methods of calibration have been proposed.

Calibration process validation

- Development of a simulation software including models of the instrument and the satellite drag-free sytem and implementation of the calibration methods
- Results compatible with the specifications

Data processing validation

- Association with a dedicated software for the EP test sessions in order to test the entire mission scenario
- Correction of the measurement with the parameters estimated during the calibration process: estimation of the EP parameter to validate the mission performance
- Influence of the numerical effects (missing data)