In-flight calibration of the MICROSCOPE space mission instrument: development of the simulator

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retour sur innovation

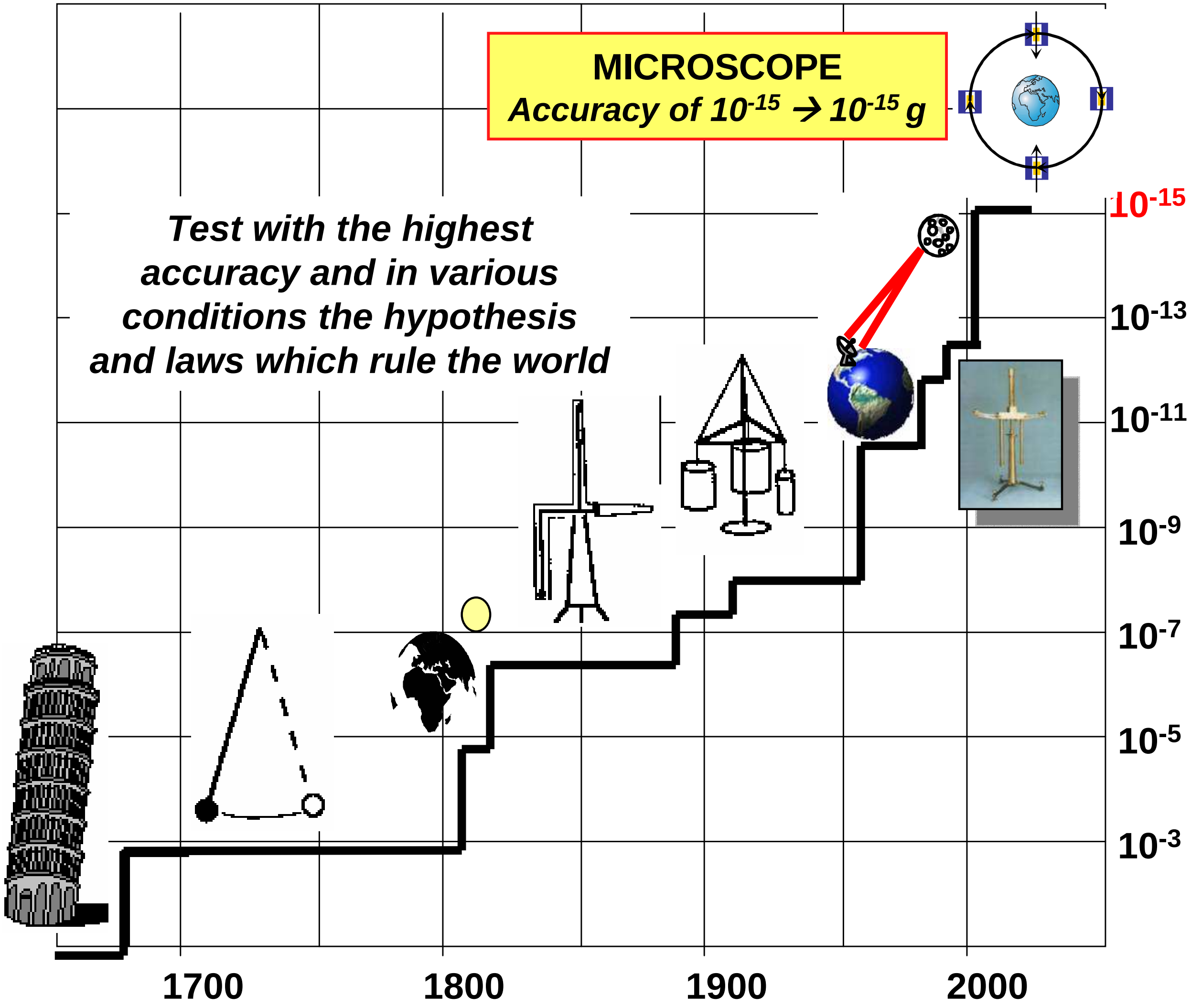
The Equivalence Principle

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

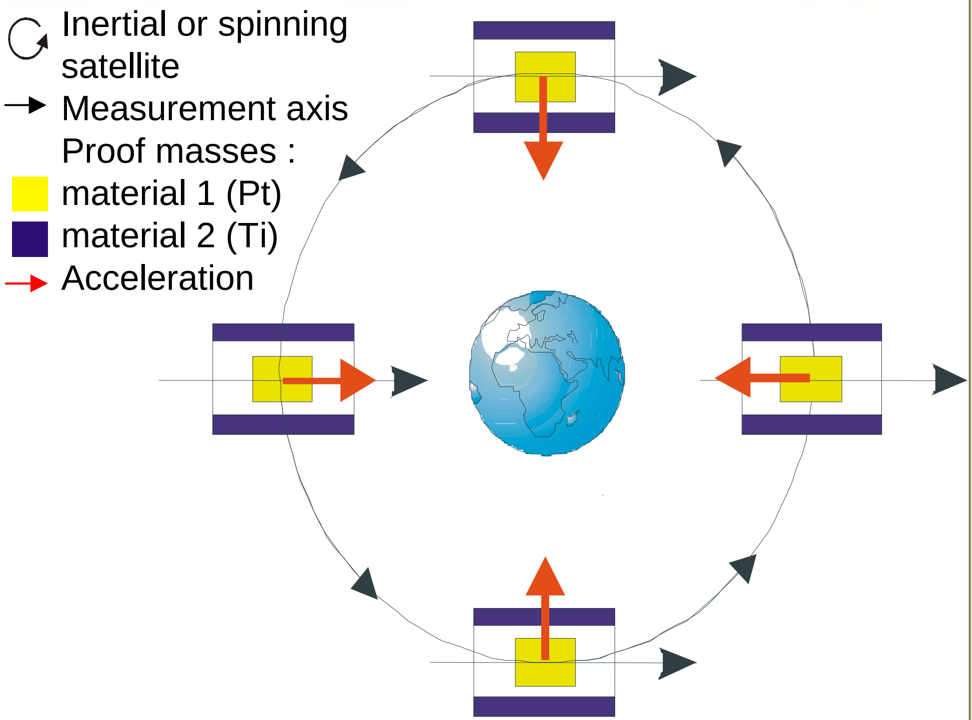
$$\frac{M_G}{M_I} = 1$$

Quantum Mechanics, Standard model: electromagnetic, strong, weak interaction
≠ Geometrical theory of the gravitation
Super-symmetry: Sparticules, LHC
String theory, Branes...
=> New interaction?
⇒Violation of the Equivalence principle?

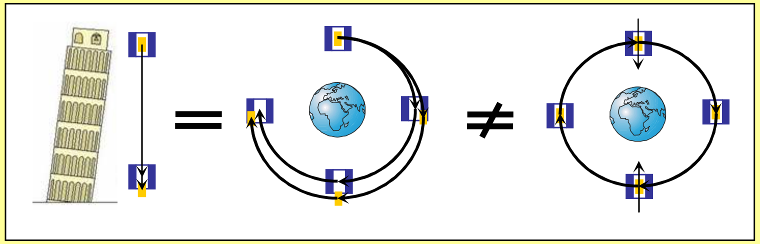
$$\frac{M_G}{M_I} = 1+\omega$$



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 **f_{ep} =**

- Inertial mode: f_{orb} = 1/orbit
- Spinning mode: 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)

Measurement principle

The accelerometer's ideal measurement is the acceleration applied to the mass to keep it centered

- Acceleration applied to a proof mass (*k*):

$$\vec{\Gamma}_{App,k} = \frac{M_{gsat}}{M_{Isat}}\vec{g}(O_{sat}) - \frac{m_{gk}}{m_{Ik}}\vec{g}(O_k) + R_{In,Cor}(\overrightarrow{O_{sat}O_k}) + \frac{\vec{F}_{NGsat}}{M_{Isat}} - \frac{\vec{F}_{Pak}}{m_{Ik}}$$

$$\frac{\vec{F}_{NGsat}}{M_{Isat}} \rightarrow \frac{\vec{F}_{extsat}}{M_{Isat}}, \quad \frac{\vec{F}_{thsat}}{M_{Isat}}$$

$$\vec{\Gamma}_{App,k} = \underbrace{\left(\frac{M_{gsat}}{M_{Isat}} - \frac{m_{gk}}{m_{Ik}}\right)\vec{g}(O_{sat}) + (\mathrm{T}-\mathrm{I})\overrightarrow{O_k O_{sat}}}_{\vec{\Gamma}_{app,k}} - 2\Omega\dot{\overrightarrow{O_k O_{sat}}} - \ddot{\overrightarrow{O_k O_{sat}}} + \frac{\vec{F}_{NGsat}}{M_{Isat}} - \frac{\vec{F}_{Pak}}{m_{Ik}}$$

- Real Measured acceleration of a proof mass (*k*):

$$\overrightarrow{\Gamma_{mes,k}} = \overrightarrow{B_{0,k}} + [M_k]\overrightarrow{\Gamma_{App,k}} + K_{2,k}\Gamma^2_{App,k} + \overrightarrow{\Gamma_{n,k}}$$

Expression of the differential measurement

The difference of measurement between the two masses gives the EP violation signal.	The test is performed at f_{ep} → the bias can be neglected

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

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

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

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

Drag-free residual — Drag-free command

$\Gamma_{mes,c}$

$\Gamma_{app,d}$

- Δ : off-centering
- K_1 : scale factor
- η : coupling
- θ : misalignement
- K_2 : quadratic terms

Contributors

- **Source of errors**: mechanical defects, gravity gradient, thermal and magnetic effects
  → **40 groups of contributors**

- Each group is specified to be < 10^{-16}m/s^{-2}

- 3 groups are explicit in the measurement equation
  - Defects between the instrument and the satellite
  - Defects between the two sensors
  - Quadratic non linearities

Budget before calibration

Group	Signal element	Parameter concerned	Contribution before calibration ($m \cdot s^{-2}$)
Defects between the instrument and the satellite	$K_{1cx} \cdot T_{xx} \cdot \Delta_x$	$K_{1cx} \cdot \Delta_x < 20.2\ \mu m$	8.4×10^{-14}
	$K_{1cx} \cdot T_{xz} \cdot \Delta_z$	$K_{1cx} \cdot \Delta_z < 20.2\ \mu m$	8.6×10^{-14}
	$K_{1cx} \cdot T_{xy} \cdot \Delta_y$	$K_{1cx} \cdot \Delta y < 20.2\ \mu m$	6×10^{-16}
	$(\eta_{cz} + \theta_{cz}) \cdot T_{yy} \cdot \Delta_y$	$\eta_{cz} + \theta_{cz} < 2.6\times10^{-3}$ rad $\Delta_y < 20\ \mu m$	8.6×10^{-16}
	$(\eta_{cy} - \theta_{cy}) \cdot T_{zz} \cdot \Delta_z$	$\eta_{cy} - \theta_{cy} < 2.6\times10^{-3}$ rad $\Delta_z < 20\ \mu m$	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} →

Specification = 3.10^{-16}
A posteriori correction is required

Calibration methods

$$\Gamma_{mes,dx} = \frac{1}{2} K_{1cx} \cdot \delta \cdot g_{x/sat} + \frac{1}{2}\begin{bmatrix} K_{1cx} \\ \eta_{cz}+\theta_{cz} \\ \eta_{cy}-\theta_{cy} \end{bmatrix}^t \cdot [T - In] \cdot \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix} + \begin{bmatrix} K_{1dx} \\ \eta_{dz}+\theta_{dz} \\ \eta_{dy}-\theta_{dy} \end{bmatrix}^t \cdot \left(\vec{\Gamma}_{res_{df}} + \vec{C}\right) + 2 \cdot K_{2cxx} \cdot \left(\Gamma_{app,dx} + b_{1dx}\right) \cdot \left(\Gamma_{res_{df},x} + C_x - b_{0cx}\right)$$

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

Signal element
$K_{1cx} \cdot \Delta_x \cdot T_{xx}$
$K_{1cx} \cdot \Delta_z \cdot T_{xz}$
$K_{1cx} \cdot \Delta_y \cdot T_{xy}$
$(\eta_{cz} + \theta_{cz}) \cdot T_{yy} \cdot \Delta_y$
$(\eta_{cy} - \theta_{cy}) \cdot T_{zz} \cdot \Delta_z$
$2 \cdot K_{1dx} \cdot \Gamma_{res_{df},x}$
$2 \cdot (\eta_{dz} + \theta_{dz}) \cdot \Gamma_{res_{df},y}$
$2 \cdot (\eta_{dy} - \theta_{dy}) \cdot \Gamma_{res_{df},z}$

Use the important value of T_{xx} and T_{xz} at $2f_{orb}$. For $K_{1cx} \cdot \Delta_x$: $\Gamma_{calib1} = 2 \cdot \Gamma_{mes,dx/\cos}(2 f_{orb}) = \hat{T}_{xx}(2 f_{orb}) \cdot K_{1cx} \cdot \Delta_x$

T_{xy} is too weak → oscillate the satellite around Y_{sat}: $\Gamma_{calib1} = 2 \cdot \Gamma_{mes,dx}(f_{cal}) = \hat{\alpha}_0 \cdot \left[\hat{T}_{yy}(DC) - \hat{T}_{xx}(DC) - \omega_{cal}^2 \right] \cdot K_{1cx} \Delta_y$

Oscillate the satellite around an axis and oscillate the mass along an other axis → Coriolis effect.

Oscillate the satellite along each axis. The measured acceleration is controlled to follow a sine

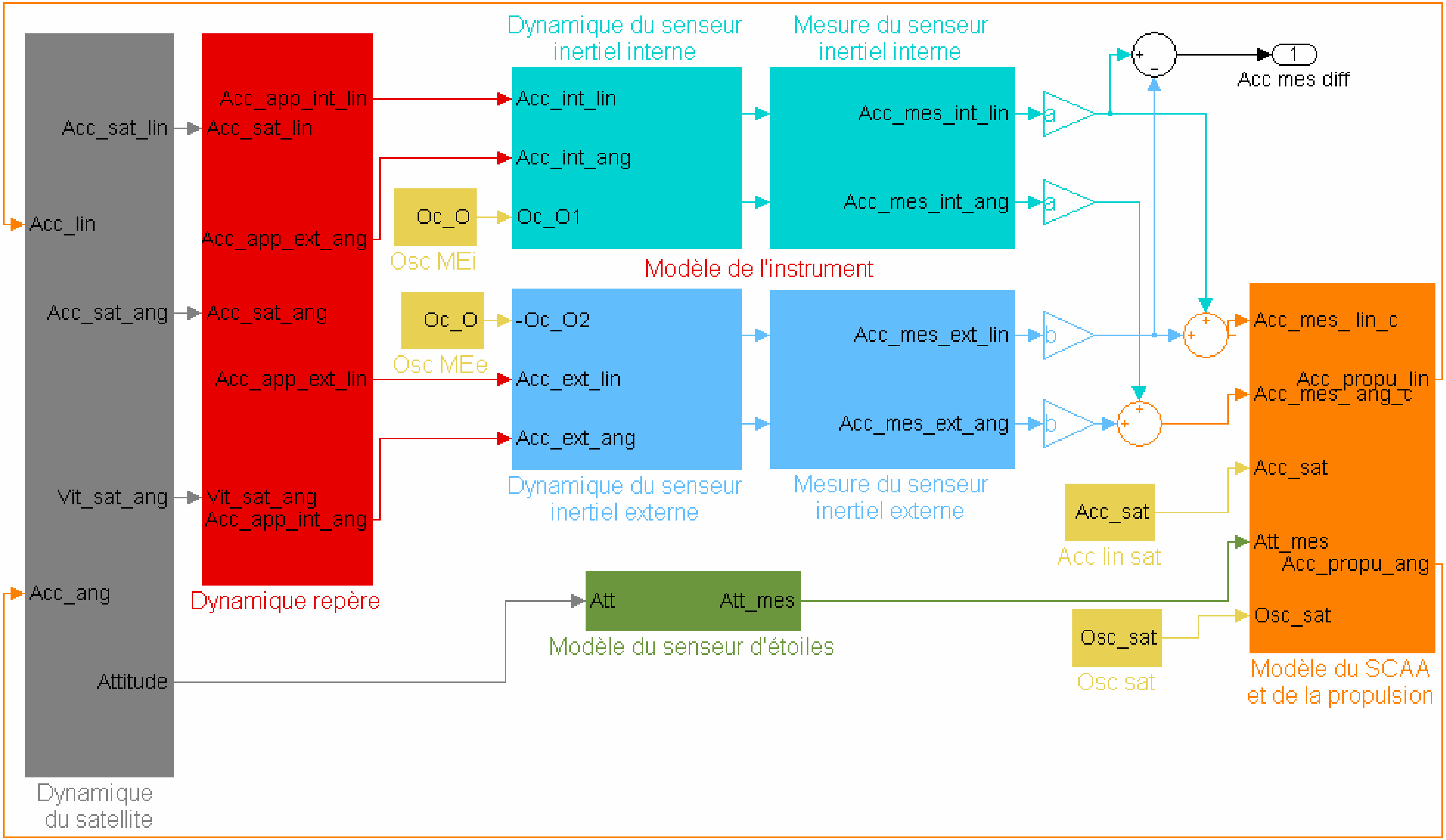
Evaluated calibration budget

T_{cal} = 10 orbits

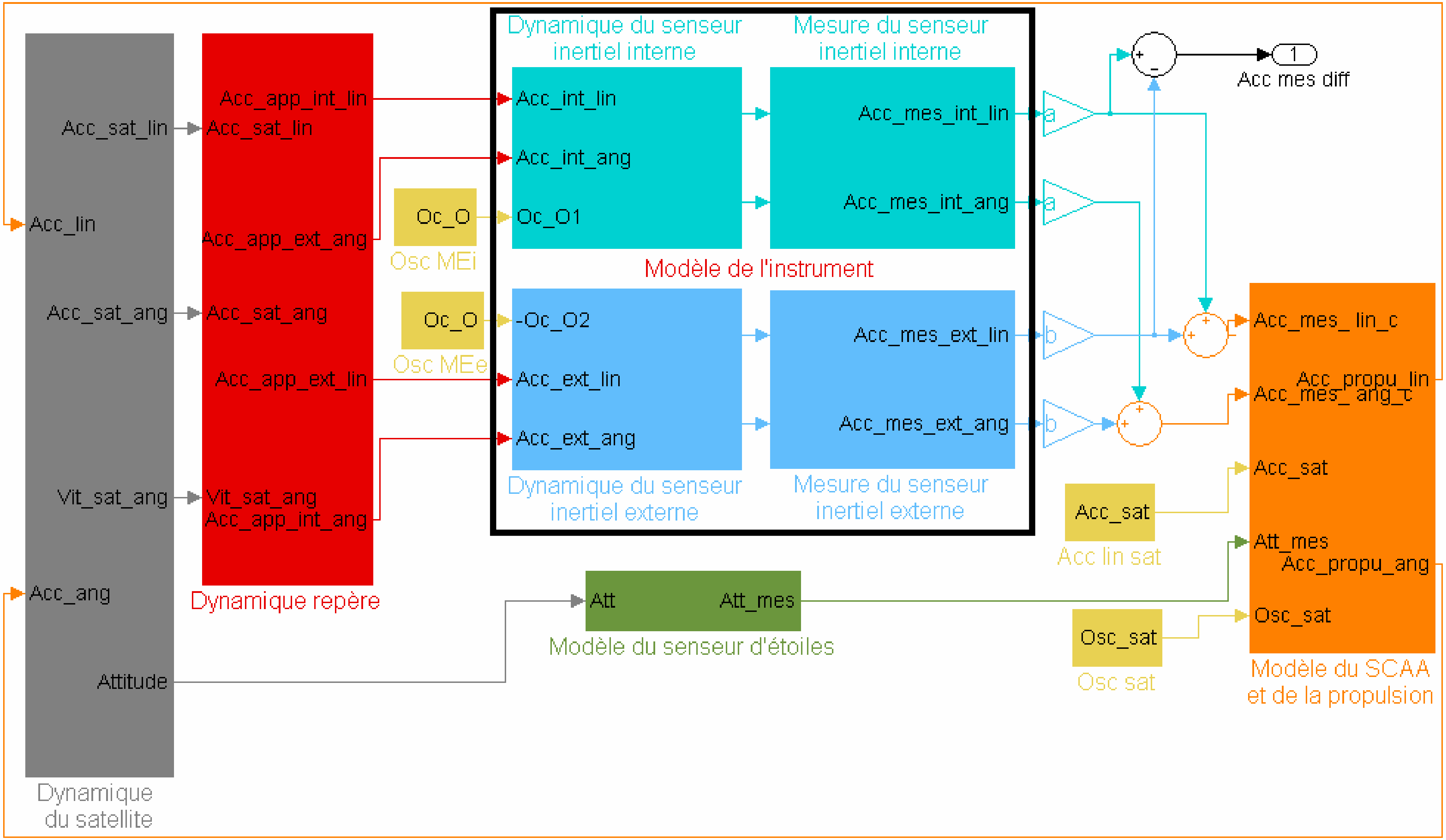
Parameter to be calibrated	Perfo. after calibration	Specification
$K_{1cx} \cdot \Delta_x$	0.10 µm	0.1 µm
$K_{1cx} \cdot \Delta_z$	0.11 µm	0.1 µm
$K_{1cx} \cdot \Delta_y$	1.2 µm	2 µm
$(\eta_{cz} + \theta_{cz})$	1.0×10^{-3} rad	9.0×10^{-4} rad
$(\eta_{cy} - \theta_{cy})$	9.5×10^{-4} rad	9.0×10^{-4} rad
$(K_{1dx} / K_{1cx})'$	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 s^2/m	250 s^2/m
K_{2cxx} / K_{1cx}^2	581.9 s^2/m	1000 s^2/m

→ Simulator to test the validity of the planned calibration procedures

Structure of the simulator



The instrument



The instrument

Simulation of the applied acceleration	
Input	Output
Acceleration at the center of the cage	Applied acceleration at the center of mass of mass k

O_k : center of mass of the proof mass k

O_c : center of mass of the cage

Shift between O_k and O_c:

→ Gravity gradient

→ Inertia

Movement of the mass k: Coriolis

$$\overrightarrow{\Gamma_{App,k}} = \overrightarrow{\Gamma_{App}}(O_c) + ([T]-[In]).\overrightarrow{O_k O_c} - [Cor].\dot{\overrightarrow{O_k O_c}}$$

Simulation of the measurement	
Input	Output
Applied acceleration at the center of mass of mass k	Measured acceleration of the mass k

$B_{0,k}$: bias

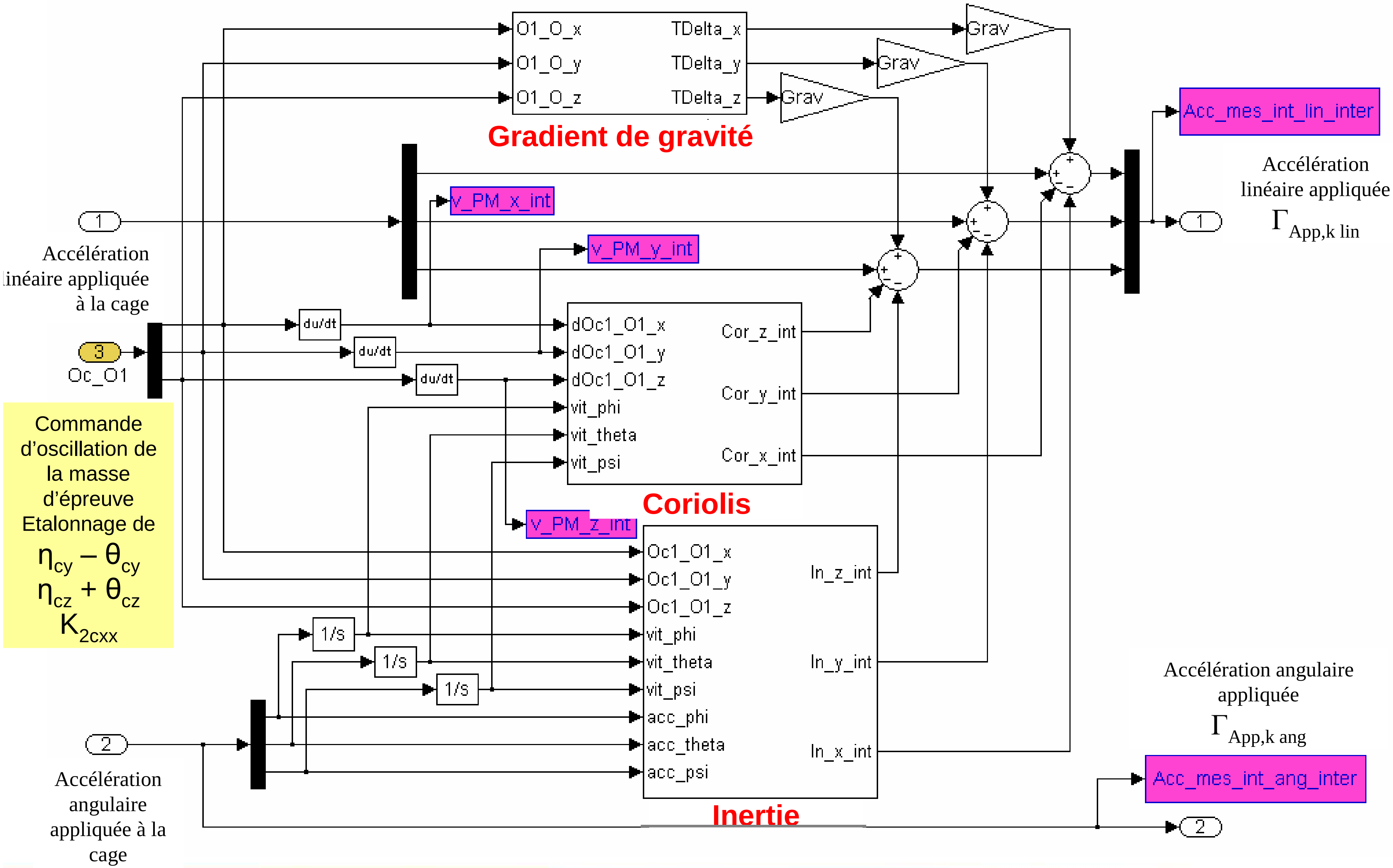
$[M_k]$: sensibility (scale factor, alignement, coupling)

$K_{2,k}$: quadratic terms

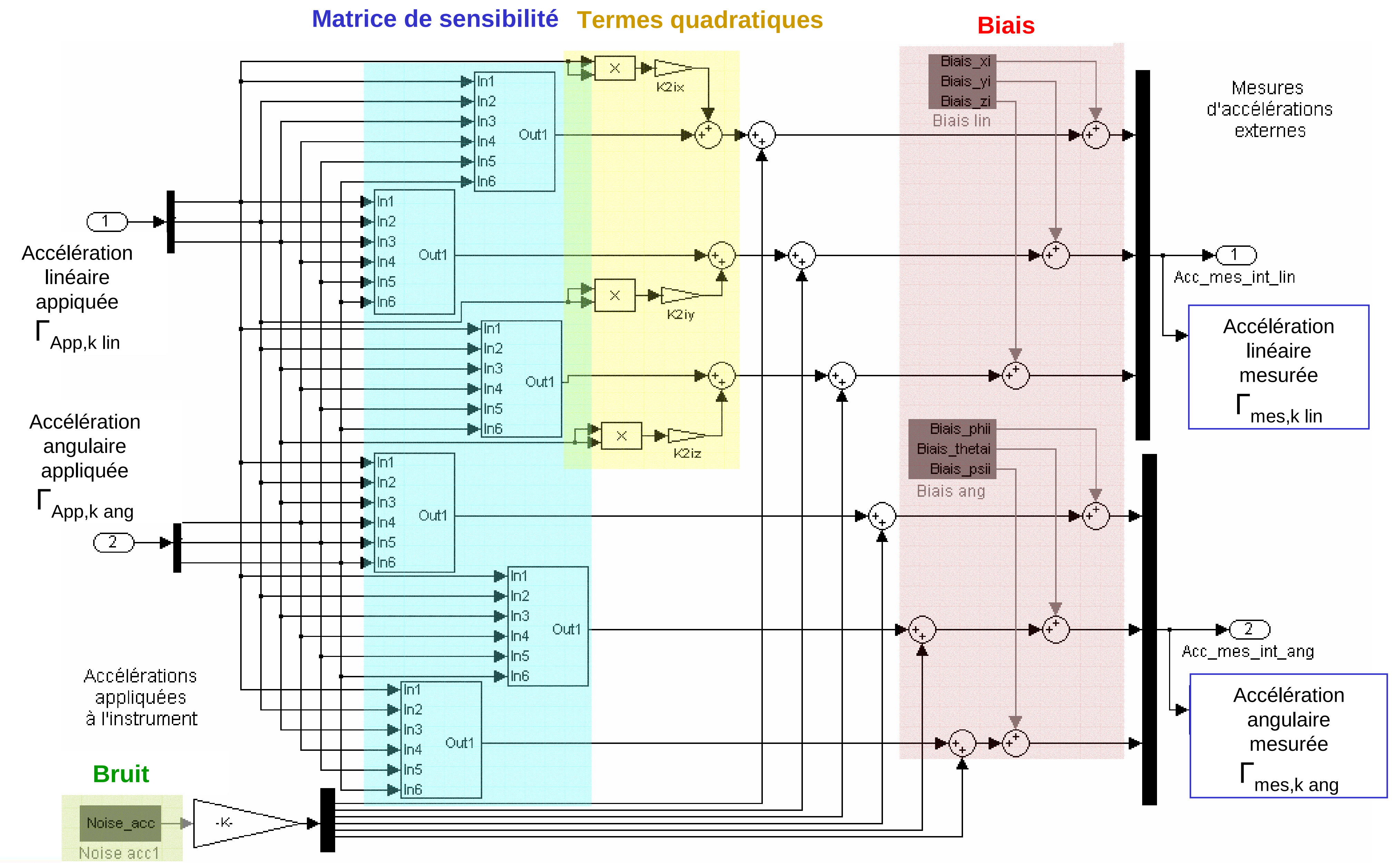
$\Gamma_{n,k}$: noise

$$\overrightarrow{\Gamma_{mes,k}} = \overrightarrow{B_{0,k}} + [M_k]\overrightarrow{\Gamma_{App,k}} + K_{2,k}\Gamma^2_{App,k} + \overrightarrow{\Gamma_{n,k}}$$

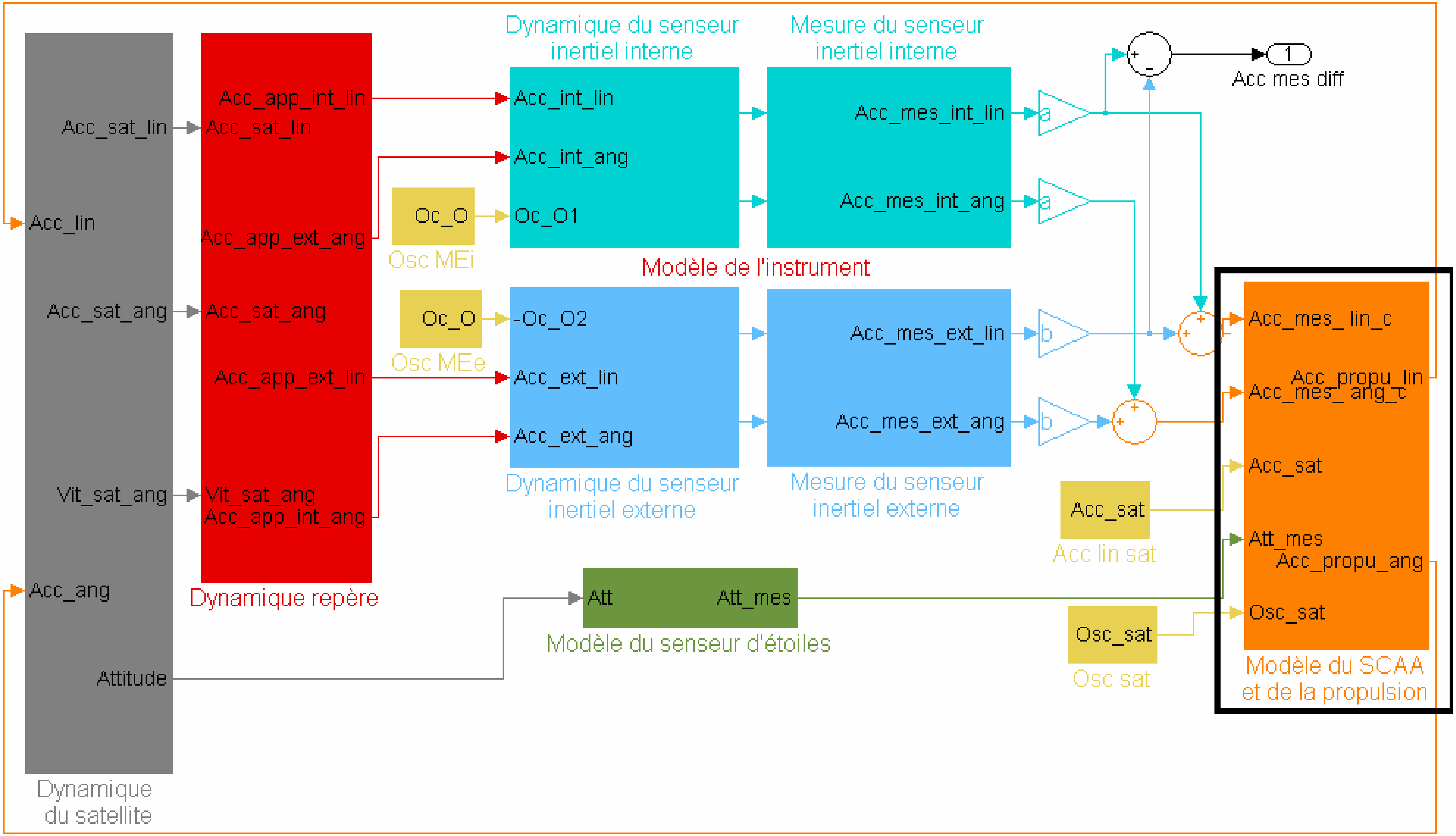
Simulation of the applied acceleration



Simulation of the measurement



SCAA and propulsion



SCAA and propulsion

SCAA: Système de contrôle d'attitude et d'altitude

Input	Output
Common acceleration of the test masses	Commanded acceleration for the propulsion

- **Altitude control**: Acceleration Γ_{DF} applied to compensate surface perturbations at the drag-free point :

$$\Gamma_{DF} = \text{transfer function}_{DF} (\Gamma_{c,mes} + C)$$

  - $\Gamma_{c,mes}$ = common acceleration at the drag free point
  - C = command of the oscillation of the satellite for calibration

- **Attitude control**: to determine the satellite's attitude, the SCAA uses a combination of :
  - The angular acceleration measured by the instrument (high frequencies)
  - The satellite's attitude measured by the star sensor (low frequencies)

Propulsion system

Input	Output
Commanded acceleration for the propulsion	Acceleration at the drag-free point

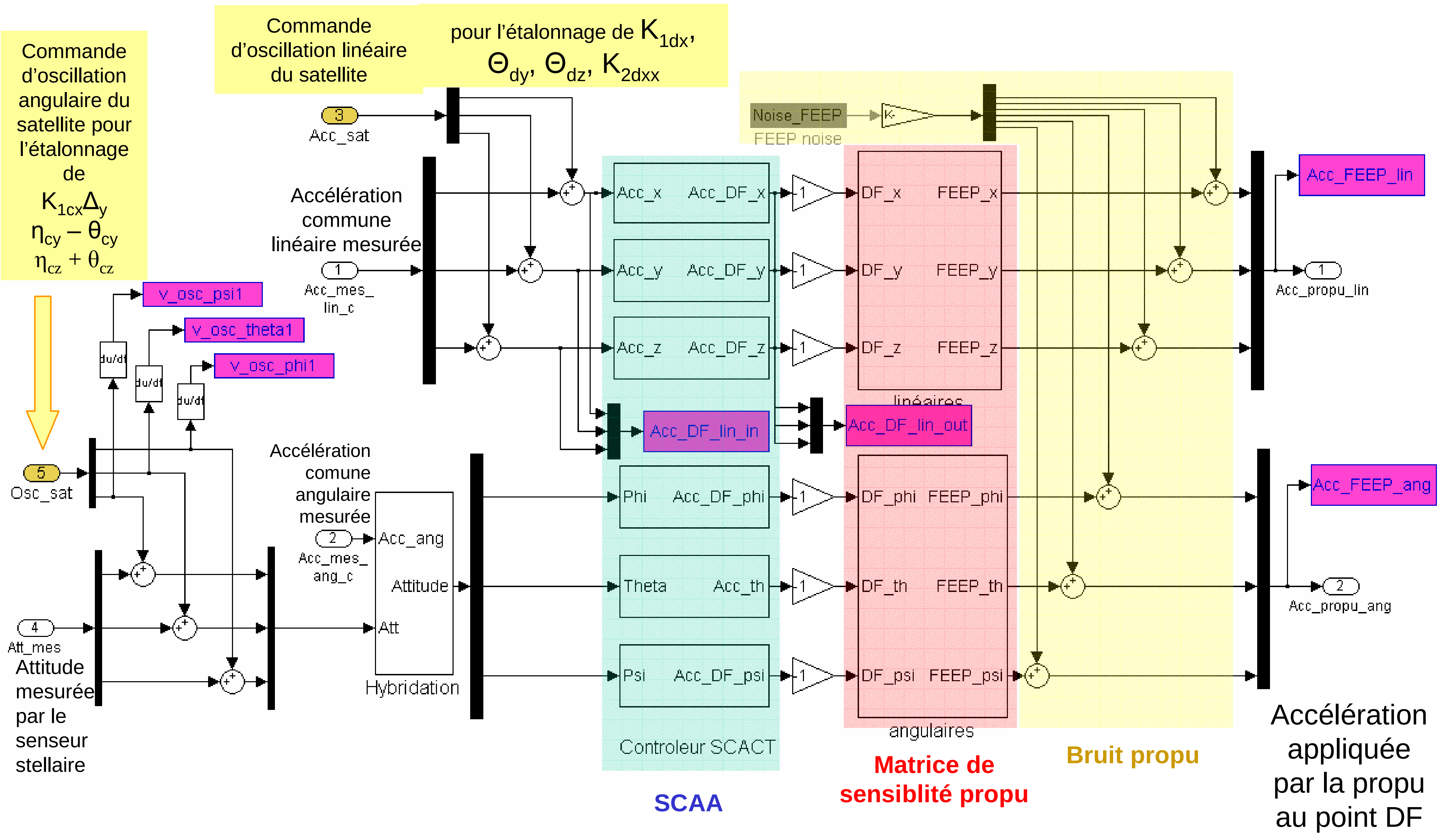
Ionic propulsors to apply the correction

Controls the linear and angular acceleration of the satellite in three directions

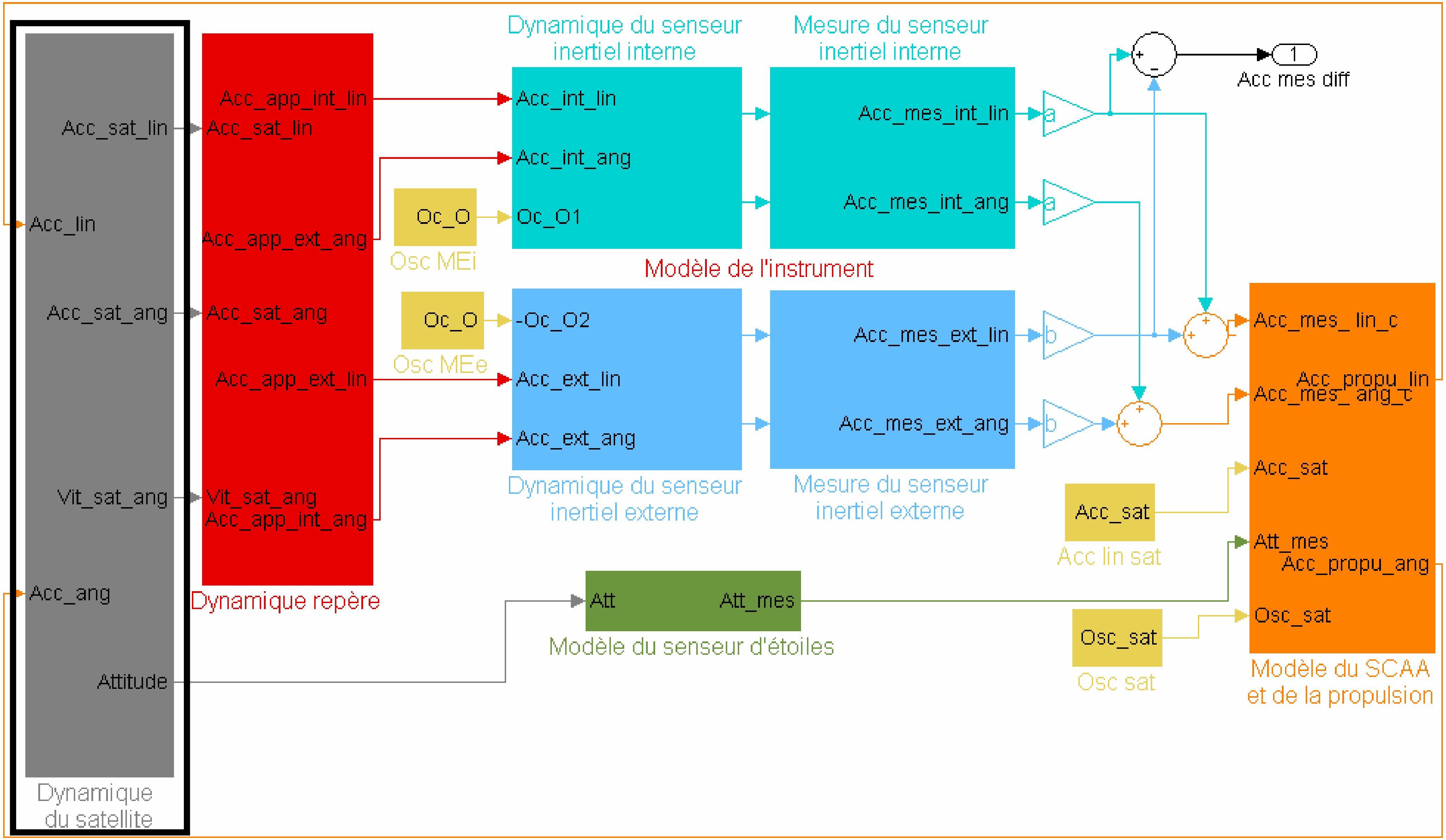
Propulsion defects : noise $\Gamma_{n,DF}$, sensibility $[M_{DF}]$

$$\overrightarrow{\Gamma_{propu}} = -[M_{DF}] \cdot \overrightarrow{\Gamma_{DF}} + \overrightarrow{\Gamma_{n,DF}}$$

SCAA and propulsion



Satellite and environment



Satellite and environment

Satellite's dynamics	
Input	Output
Acceleration applied by the propulsion	Satellite's acceleration
•Data files generated by the OCA, corresponding to the expected trajectory and orientation of the satellite: Non-gravitationnal accelerations • solar radiation • drag → added to the applied acceleration	

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. The calibration accuracy has been analytically evaluated.
  - Development of a software simulator including models of the instrument and the satellite drag-free sytem, and simulation of the calibration processes to validate the results.
- Next step
  - Compare the results of the simulator with the analytical results
  - Association with a dedicated software for the EP test sessions, developped at OCA

→ the two simulators will allow to test the entire mission scenario