Scientific data processing for the MICROSCOPE space experiment

E. Hardy, Q. Baghi, J. Berge, R. Chhun, M. Rodrigues, P. Touboul (ONERA), G. Métris (OCA)

MICROSCOPE Colloquium III

ONERA
THE FRENCH AEROSPACE LAB

retour sur innovation

Data levels

Operational — N0

data formating

Acceleration measurement per inertial sensor — N1

half-sum

half-difference

Acceleration measurement common / differential — N2

calibration with the last calibration phase

most pertinent calibration

a

Missing, saturated and abnormal data points replaced with interpolated values

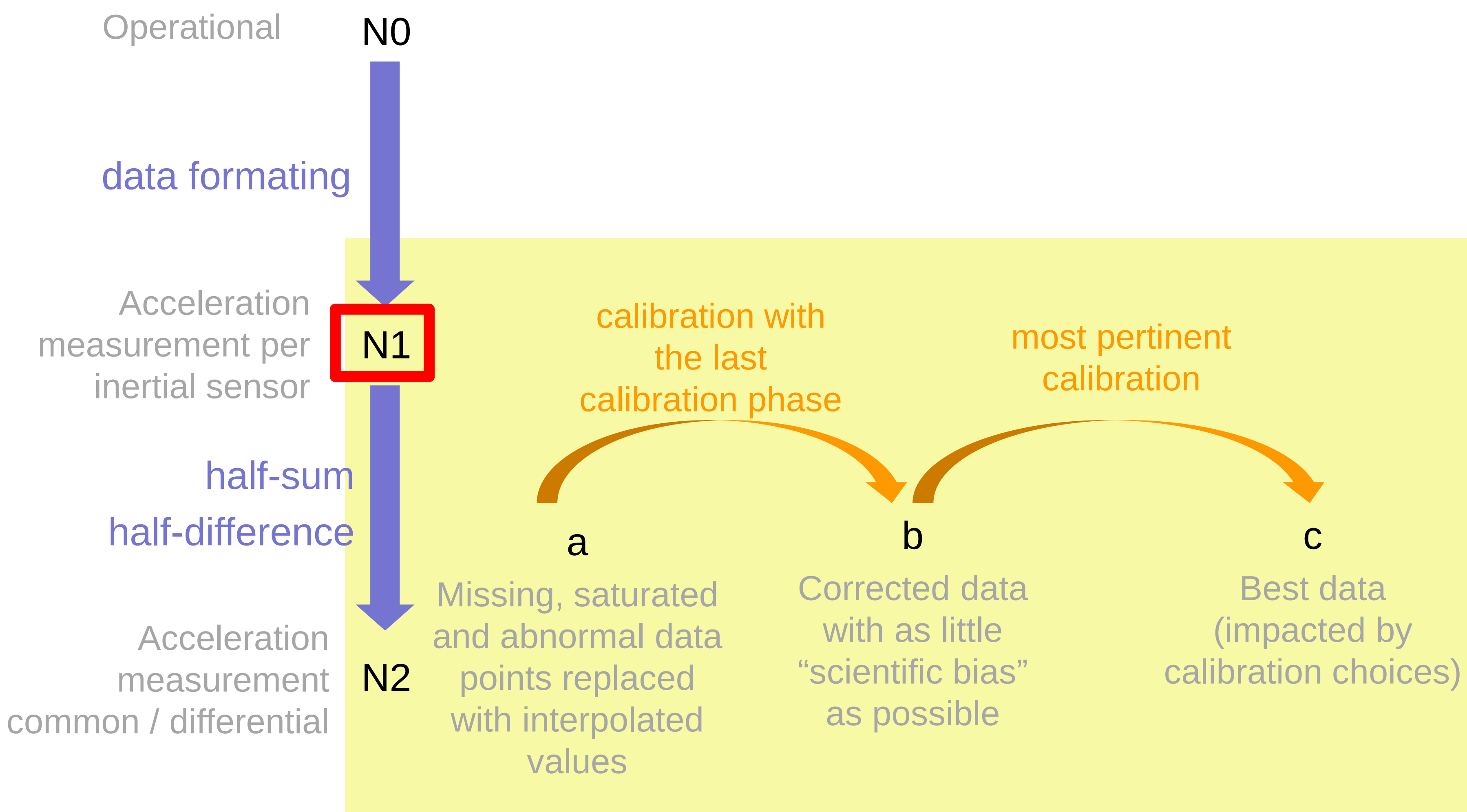
b

Corrected data with as little “scientific bias” as possible

c

Best data (impacted by calibration choices)

Data levels

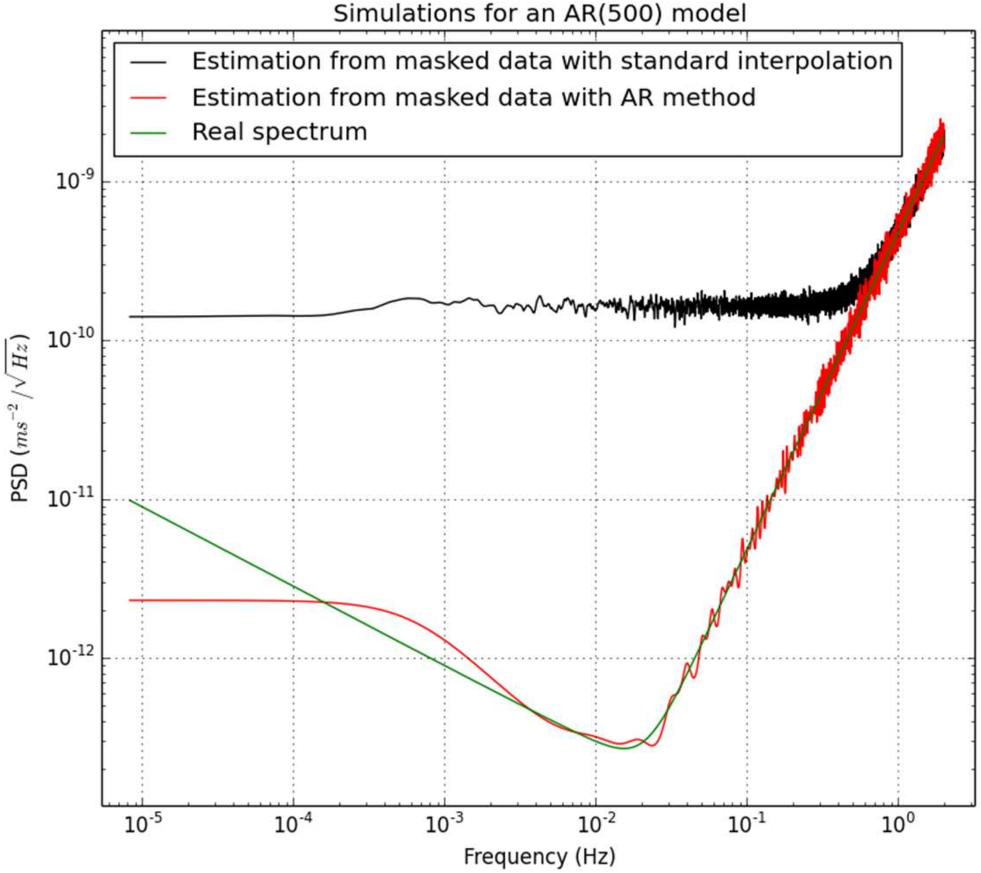


ONERA THE FRENCH AEROSPACE LAB

- **Long duration loss:**
  - **Teletransmission errors**
    - **frequency**: very few events because the TM is sent again at the next opportunity
    - **duration**: from seconds to hours
- **Very short event:**
  - **Micro-meteorites impacts**
    - **frequency**: about 10 events per orbit
  - **Coating cracking**
    - due to temperature changes (Earth / Space vacuum)
    - **frequency**: for each of the four satellite sides, about 6 times when the side faces the Earth
  - **Tank cracking**
    - depends on gas pressure
    - **frequency**: for each of the 6 tanks, about 43 times/orbit

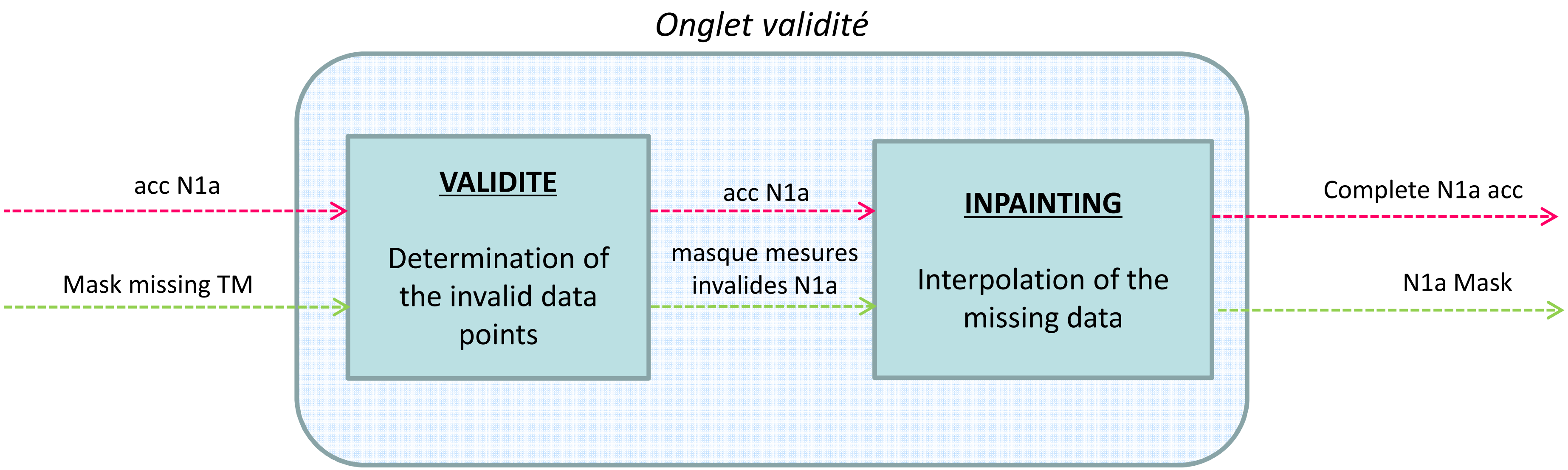
N2a data: measurement losses

- **Noise dramatically increased**
- Replacement of the missing data by an interpolated value → Inpainting algorithm: representation of the data in a dictionary where complete data are sparse and incomplete data are less sparse.
- Estimation of the noise DSP in order to weigh the measurement



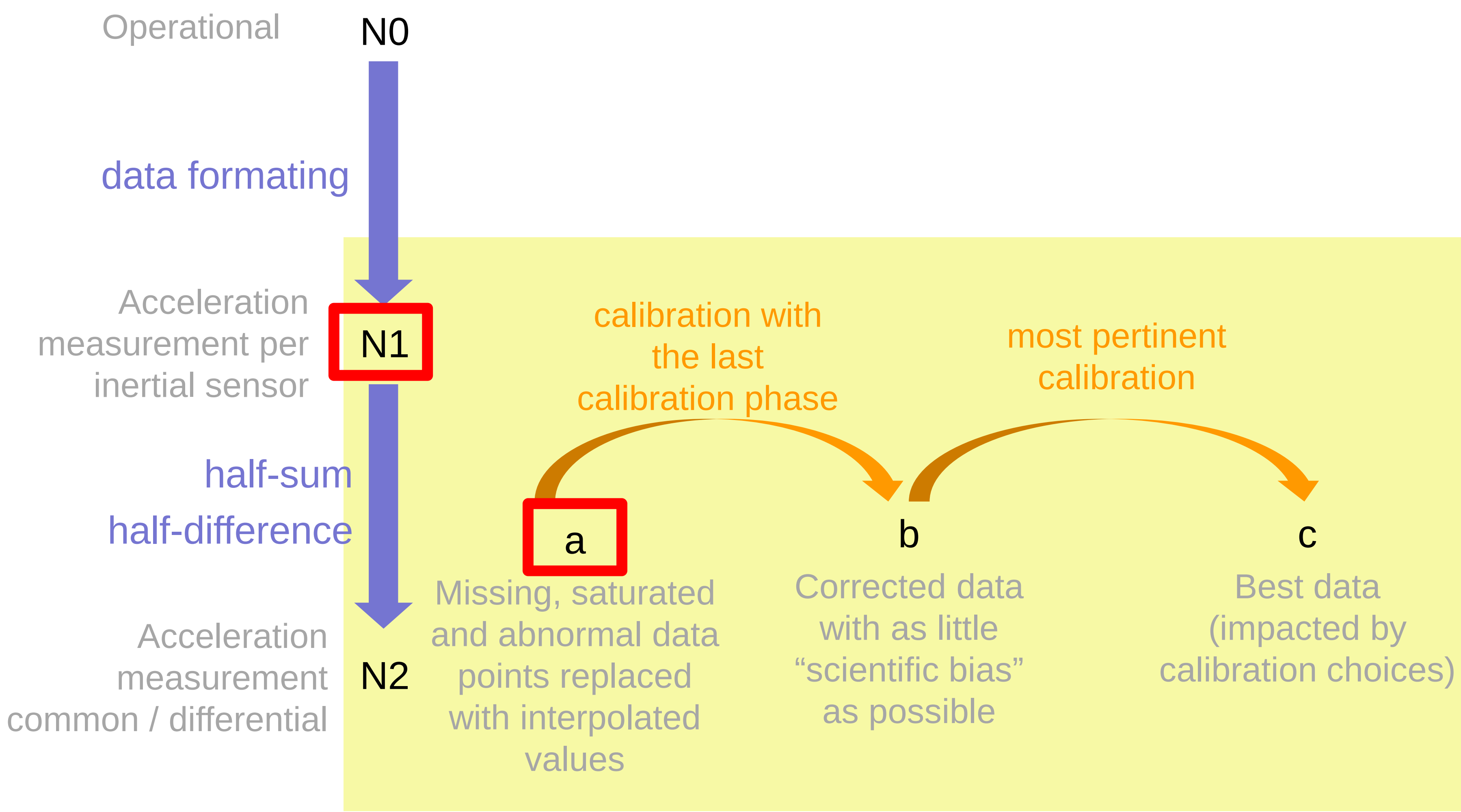
<u>**see next presentation !**</u>

N1a data

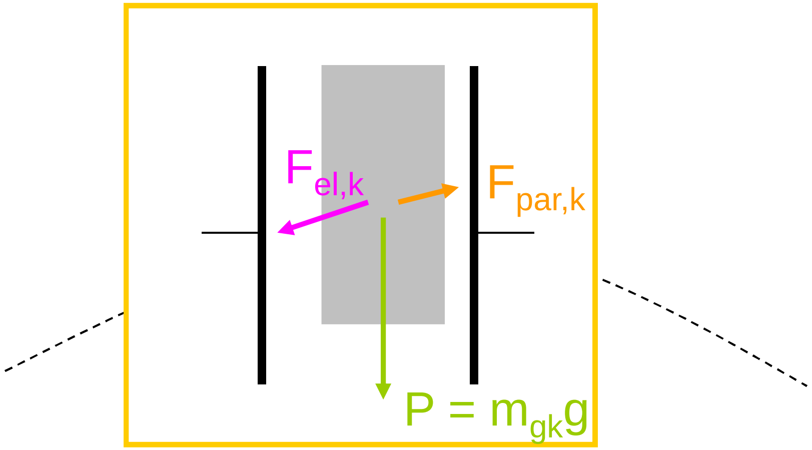


Onglet validité
acc N1a
Mask missing TM
VALIDITE
Determination of the invalid data points
acc N1a
masque mesures invalides N1a
INPAINTING
Interpolation of the missing data
Complete N1a acc
N1a Mask

Data levels


Operational
N0
data formating
Acceleration measurement per inertial sensor
N1
half-sum
half-difference
Acceleration measurement common / differential
N2
calibration with the last calibration phase
most pertinent calibration
a
b
c
Missing, saturated and abnormal data points replaced with interpolated values
Corrected data with as little “scientific bias” as possible
Best data (impacted by calibration choices)

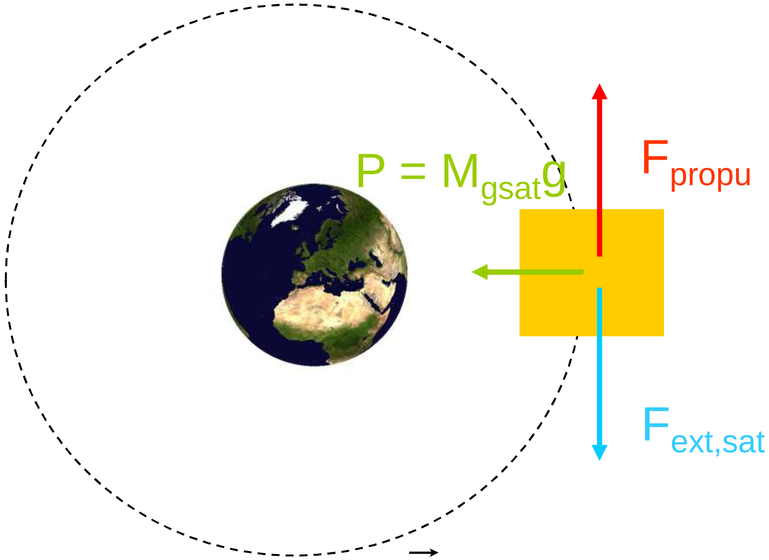
Test mass k / satellite



- Electrostatic force: $m_{Ik}\vec{\Gamma}_{App,k}$
- Weight: $m_{gk}\vec{g}(O_k)$
- Parasitic forces: $m_{Ik}\vec{\Gamma}_{Par,k}$
- Inertia: $\vec{f}_{ie} = -m_{Ik}\left(\ddot{\overrightarrow{O_{sat}O}} + [In]\cdot\overrightarrow{O_{sat}O_k}\right)$
- Coriolis : $\vec{f}_{ic} = -m_{Ik}[Cor]\cdot\dot{\overrightarrow{O_{sat}O_k}}$

$$m_{Ik}\ddot{\overrightarrow{O_{sat}O_k}} = m_{gk}\vec{g}(O_k) + m_{Ik}\vec{\Gamma}_{App,k} + m_{Ik}\vec{\Gamma}_{Par,k}$$
$$-m_{Ik}[In]\cdot\overrightarrow{O_{sat}O_k} - m_{Ik}[Cor]\cdot\dot{\overrightarrow{O_{sat}O_k}} - m_{Ik}\ddot{\overrightarrow{O_{sat}O}}$$

Satellite / geocentric frame



- Weight: $M_{gsat}\vec{g}(O_{sat})$
- Non-gravitational force: $M_{Isat}\vec{\Gamma}_{ng,sat}$
  - → propulsion thrust
  - → external perturbations

$$M_{Isat}\ddot{\overrightarrow{O_{sat}O}} = M_{gsat}\vec{g}(O_{sat}) + M_{Isat}\vec{\Gamma}_{ng,sat}$$

N1a data: instrumental measurement

Ideal accelerometer measurement: electrostatic acceleration applied to the test mass k to keep it centered

$$\vec{\Gamma}_{App,k} = \frac{M_{gsat}}{M_{Isat}}\vec{g}(O_{sat}) - \frac{m_{gk}}{m_{Ik}}\vec{g}(O_k) + \vec{\Gamma}_{ng,sat} - \vec{\Gamma}_{Par,k} + [In]\overrightarrow{O_{sat}O_k} + [Cor]\cancel{\dot{\overrightarrow{O_{sat}O_k}}} + \cancel{\ddot{\overrightarrow{O_{sat}O_k}}}$$

$$\vec{\Gamma}_{App,k} = \left(\frac{M_{gsat}}{M_{Isat}} - \frac{m_{gk}}{m_{Ik}}\right)\vec{g}(O_{sat}) + ([T]-[In])\cdot\overrightarrow{O_kO_{sat}} + \vec{\Gamma}_{ng,sat} - \vec{\Gamma}_{Par,k}$$

Real accelerometer measurement

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

b_0 : bias
[M] : sensitivity matrix (scale factors, misalignement, coupling)
$K_{2,k}$: quadratic term
$\Gamma_{n,k}$: noise

N2a data: instrumental measurement

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

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

Δ : off-centering
K_1 : scale factor
η : coupling

θ : misalignement
K_2 : quadratic term

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

Gravity gradient

Inertia gradient

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

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

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

N2a data: instrumental measurement

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

ACTENS : V is computed thanks to a the GRIM4 model of the Earth gravity potential

gravitational field : $g_i = \frac{\partial V}{\partial x_i}$ gravity gradient : $T_{ij} = \frac{\partial^2 V}{\partial x_i \partial x_j}$

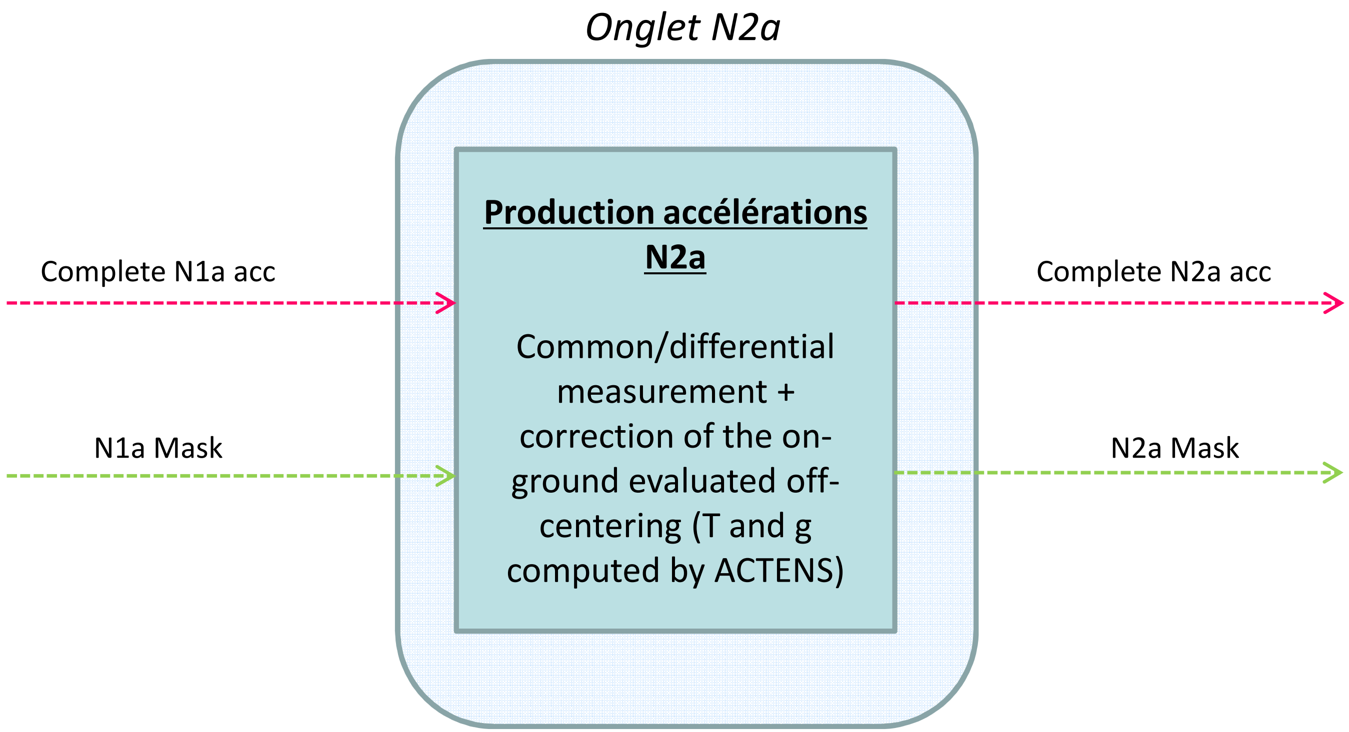
Inertia gradient

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

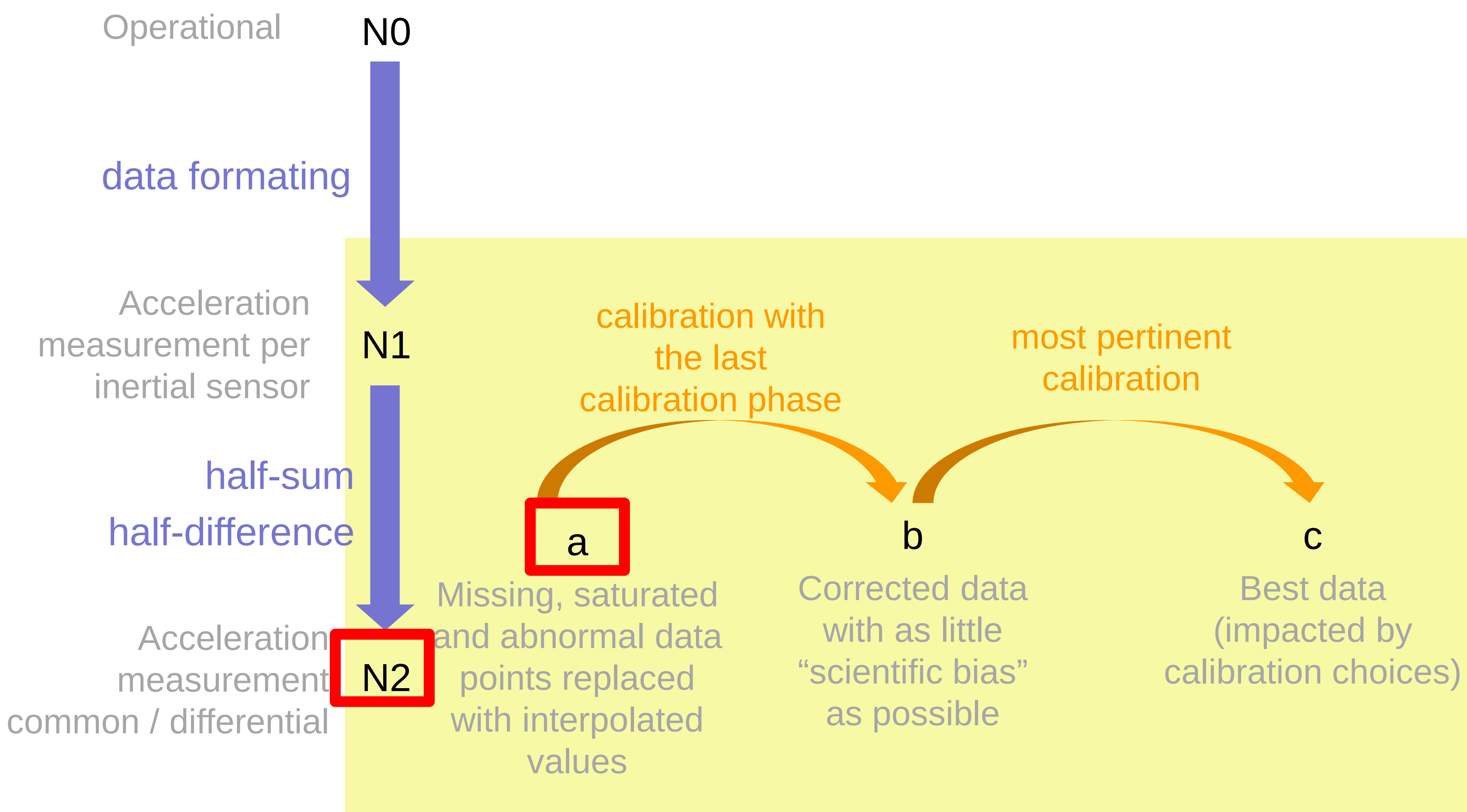
$$+ \begin{bmatrix} K_{1dx} \\ \eta_{dz} + \theta_{dz} \\ \eta_{dy} - \theta_{dy} \end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + C_x) + 2 \cdot K_{2cxx} \cdot (\Gamma_{app,dx} + b_{1dx}) \cdot (\Gamma_{res_{df},x} + C_x - b_{0cx})$$

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

From N1a to N2a data



Data levels



Operational
N0
data formating
Acceleration measurement per inertial sensor
N1
half-sum
half-difference
Acceleration measurement common / differential
N2
calibration with the last calibration phase
most pertinent calibration
a
b
c
Missing, saturated and abnormal data points replaced with interpolated values
Corrected data with as little “scientific bias” as possible
Best data (impacted by calibration choices)

Necessity of the in-orbit calibration

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

Gravity gradient — Inertia gradient

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

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

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

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

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

Error budget before calibration: 1.10^{-13} m.s^{-2}

→ an in-orbit calibration is necessary

In-orbit calibration

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

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

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

- **$K_{1cx}\Delta_x$** et **$K_{1cz}\Delta_z$** : exploitation des signaux forts T_{xx} et T_{xz} à $2f_{orb}$

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

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

- **Paramètres de la matrice de sensibilité en mode différentiel (K_{1dx}, $\eta_{dz}+\theta_{dz}$, $\eta_{dy}-\theta_{dy}$) :** oscillation du satellite le long de X, Y ou Z à travers la commande C du système de compensation de traînée

$$\Gamma_{mes,dx}(f_{cal/lin}) = K_{1dx}\cdot\Gamma_{mes,cx}(f_{cal/lin})$$

In-orbit calibration

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

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

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

- **$K_{1cx}\Delta_x$** et **$K_{1cx}\Delta_z$** : exploitation des signaux forts T_{xx} et T_{xz} à $2f_{orb}$

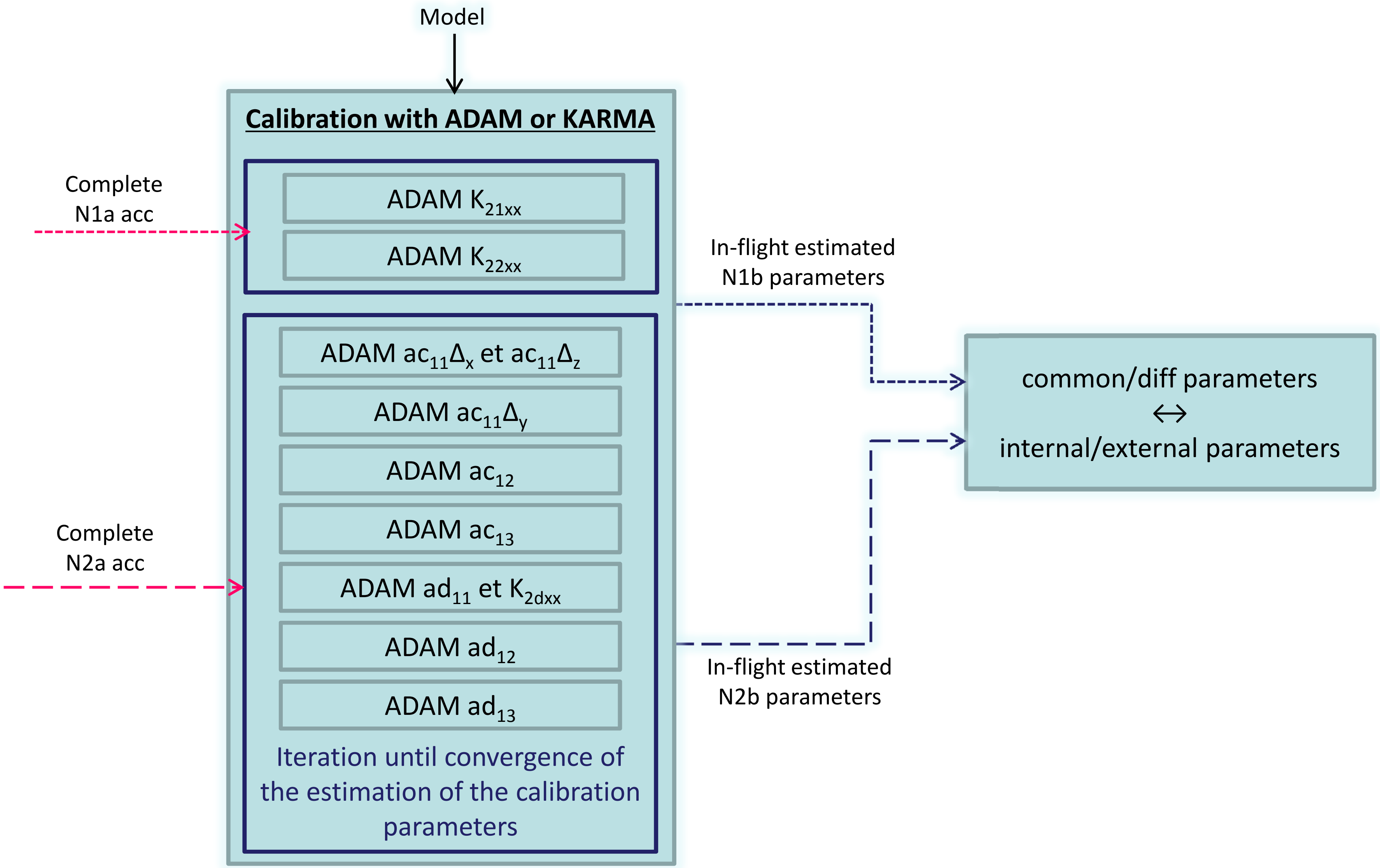
Composante cosinus : $\Gamma_{mes,dx/\cos}(2f_{orb}) = \frac{1}{2}K_{1cx}\cdot T_{xx}(2f_{orb})\cdot\Delta_x$

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

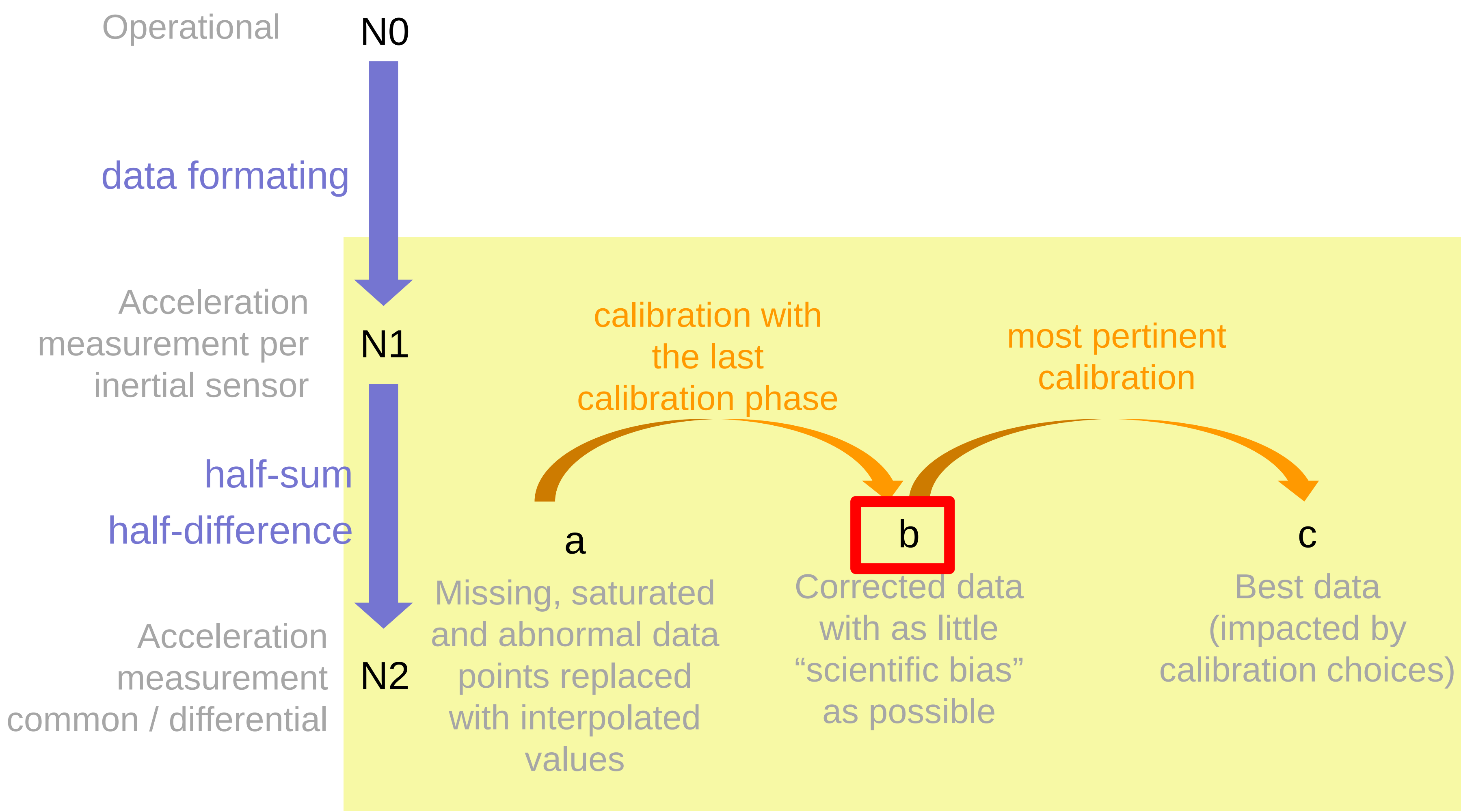
- **Paramètres de la matrice de sensibilité en mode différentiel (K_{1dx}, η_{dz} + θ_{dz},η_{dy} - θ_{dy}) :** oscillation du satellite le long de X, Y ou Z à travers la commande C du système de compensation de traînée

$$\Gamma_{mes,dx}(f_{cal/lin}) = K_{1dx}\cdot\Gamma_{mes,cx}(f_{cal/lin})$$

From N1a and N2a accelerations to N1b and N2b parameters

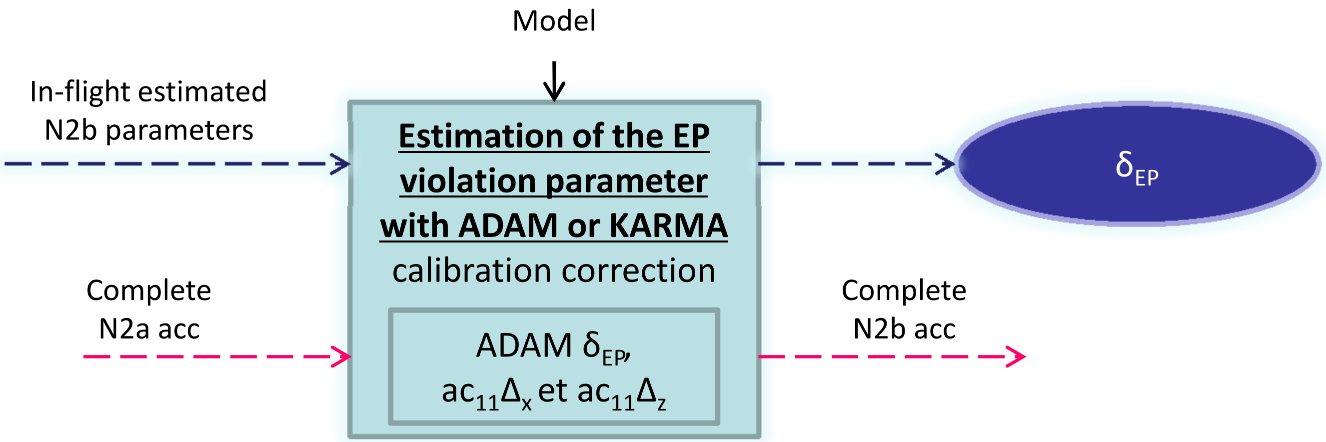


Data levels



ONERA THE FRENCH AEROSPACE LAB

From N2b data: EP estimation



- **Measurement model:** $\Gamma_{mes,dx}(t) = \sum a_k(t) x_k$

- **Measurement correction:** $\Gamma_{mes,dx/corr}(t) = \sum a_k(t)(x_k - x_{k0})$

- **Least squares inversion:** $Y = A \cdot X \rightarrow \hat{X} = (A^T \cdot P \cdot A)^{-1} \cdot A^T \cdot P \cdot Y$

Estimator with minimal variance if: $P^T \cdot P = [\sigma^2]^{-1}$
Problem: - σ is not known
- difficult inversion
→ Fourier Transform to select interesting frequencies only

Data levels

Operational — N0

data formating

Acceleration measurement per inertial sensor — N1

half-sum

half-difference

Acceleration measurement common / differential — N2

calibration with the last calibration phase

most pertinent calibration

a — Missing, saturated and abnormal data points replaced with interpolated values

b — Corrected data with as little “scientific bias” as possible

c — Best data (impacted by calibration choices)