# MICROSCOPE data processing and analysis, missing data and inpainting

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return on innovation

# Data analysis: what do we measure?

EP violation signal

$$\delta = \frac{m_{g2}}{m_{i2}} - \frac{m_{g1}}{m_{i1}}$$

$$\vec{\Gamma}_{\mathrm{meas,d}} = [\mathcal{M}_c]\left(\delta\vec{g} + ([\mathcal{T}]-[\mathcal{I}n])\vec{\Delta} - 2[\Omega]\dot{\vec{\Delta}} - \ddot{\vec{\Delta}}\right) + \overrightarrow{K_{0,d}} + [\mathcal{M}_d]\left(\vec{\Gamma}_{\mathrm{app,c}} + \frac{\vec{F}_{ext}}{M_{Isat}} + \frac{\vec{F}_{th}}{M_{Isat}}\right) + \frac{1}{2}K_{2,i}\Gamma^2_{App,i} - \frac{1}{2}K_{2,j}\Gamma^2_{App,j} + \vec{\Gamma}_{\mathrm{n,d}} + [\mathcal{C}_d]\dot{\vec{\Omega}}$$

- Earth gravity gradient tensor: *model, S/C position and attitude*
- Instrument's moments of inertia: *minimized by AOCS from SST and instr. data*
- Separation between test masses' centers: *minimized by instrument design*
- Coriolis acceleration
- Relative acceleration
- Non-gravitational accelerations => *drag-free system*
- Bias difference: *limited thermal fluctuations*
- Differential mode sensitivity matrix: *estimated by in-flight calibration*
- Common mode sensitivity matrix: *estimated by in-flight calibration, limited by design*
- Quadratic factor
- Total acceleration applied to proof-mass
- Instrument noise
- Angular-linear couplings

$$\begin{pmatrix} K_{cx} & \eta_{cz}+\theta_{cz} & \eta_{cy}-\theta_{cy} \\ \eta_{cz}-\theta_{cz} & K_{cy} & \eta_{cx}+\theta_{cx} \\ \eta_{cy}+\theta_{cy} & \eta_{cx}-\theta_{cx} & K_{cz} \end{pmatrix}$$

- Scale factor
- Coupling between instrument's axes
- Instrument's axes / satellite reference frame alignment

# How to extract the information?

Least-Square estimation after correction / modelling of nuisance parameters

$$
\begin{aligned}
2\Gamma_x^{(d)} \simeq\, & 2Bd_x \\
& + ac_{11}\left[\delta g_x + (T_{xx} - In_{xx})\Delta_x + (T_{xy} - In_{xy})\Delta_y + (T_{xz} - In_{xz})\Delta_z\right] \\
& + ac_{12}\left[\delta g_y + (T_{yx} - In_{yx})\Delta_x + (T_{yy} - In_{yy})\Delta_y + (T_{yz} - In_{yz})\Delta_z\right] \\
& + ac_{13}\left[\delta g_z + (T_{zx} - In_{zx})\Delta_x + (T_{zy} - In_{zy})\Delta_y + (T_{zz} - In_{zz})\Delta_z\right] \\
& + ac_{11}\left(2\Omega_z\dot{\Delta}'_y - 2\Omega_y\dot{\Delta}'_z - \ddot{\Delta}'_x\right) \\
& - 2\theta_{c,x}\left(\Omega_y\dot{\Delta}'_y + \Omega_z\dot{\Delta}'_z\right) - 2ac_{13}\Omega_x\dot{\Delta}'_y + 2ac_{12}\Omega_x\dot{\Delta}'_z \\
& + \frac{K_{21,xx}}{K_{1,x}^2}\left(\Gamma_x^{(1)} - B1_x\right)^2 - \frac{K_{22,xx}}{K_{2,x}^2}\left(\Gamma_x^{(2)} - B2_x\right)^2 \\
& + 2ad_{11}\left(\Gamma_x^{(c)} - Bc_x\right) + 2ad_{12}\left(\Gamma_y^{(c)} - Bc_y\right) + 2ad_{13}\left(\Gamma_z^{(c)} - Bc_z\right) \\
& + 2nd_{11}\dot{\Omega}_x + 2nd_{12}\dot{\Omega}_y + 2nd_{13}\dot{\Omega}_z
\end{aligned}
$$

Estimated through calibration

Measured and/or computed

Negligible at $f_{EP}$

*Slide courtesy G. Métris*

# Instrument's noise spectral density

Touboul 2009

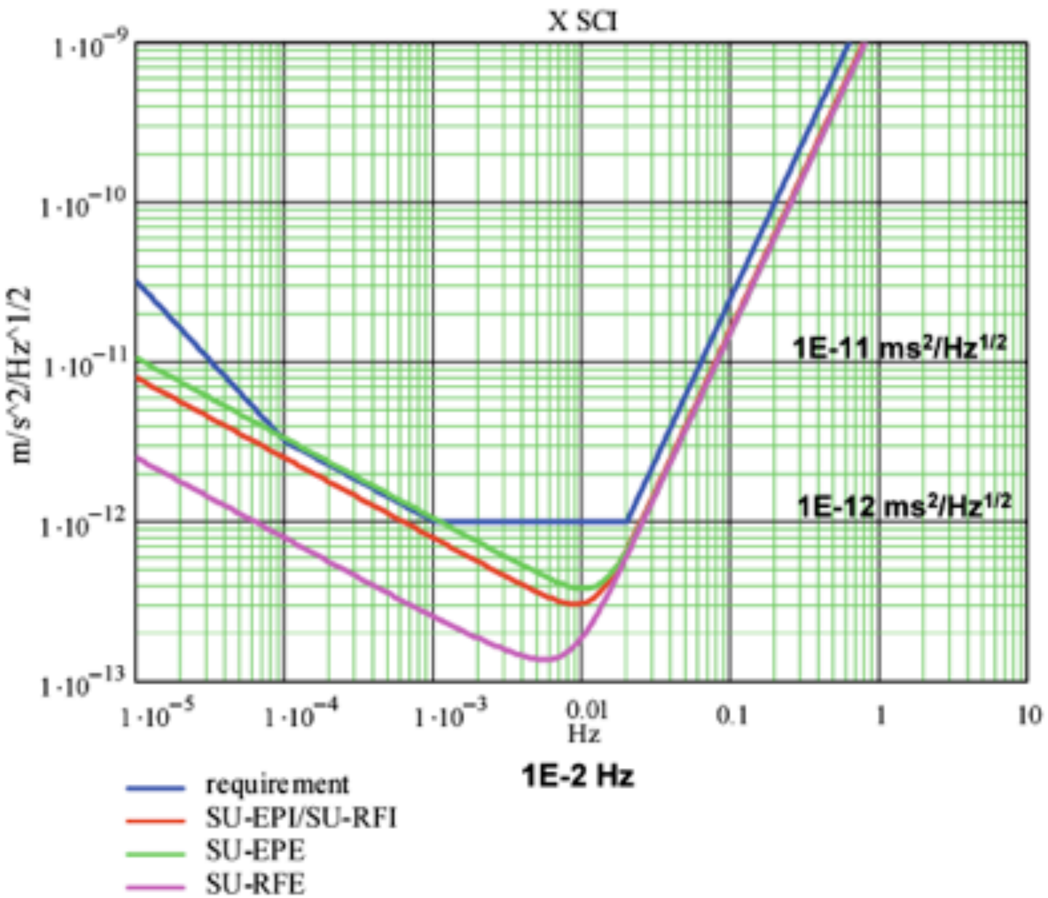
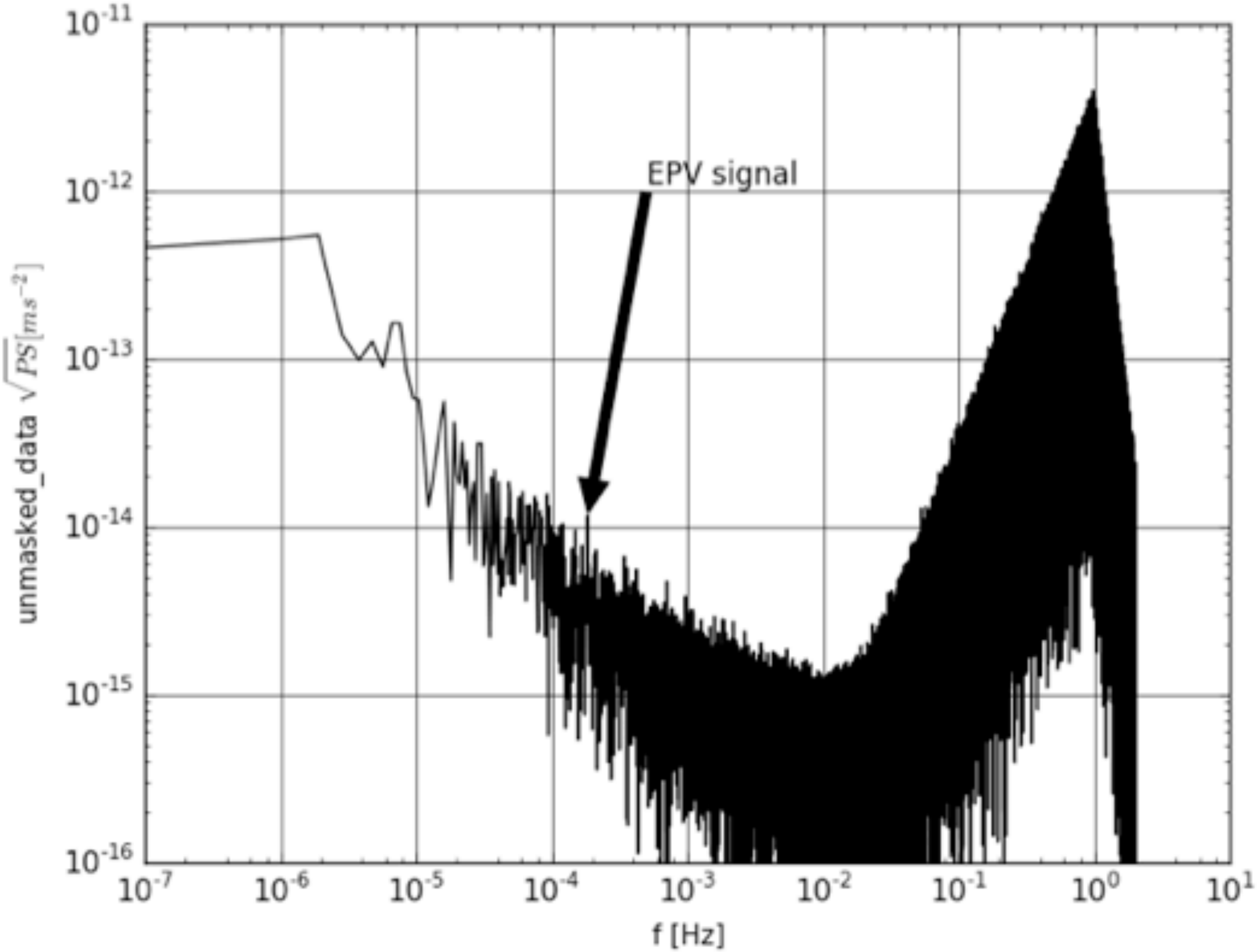



**Fig. 4** $(PSD)^{1/2}$ expressed in $ms^{-2}Hz^{-1/2}$ of all inertial sensors: Platinum external mass (*in purple*), Platinum internal mass (*in red*), Titanium external mass (*in green*), objectives to be reached (*in blue*)

# With nuisance parameters perfectly calibrated / corrected for...

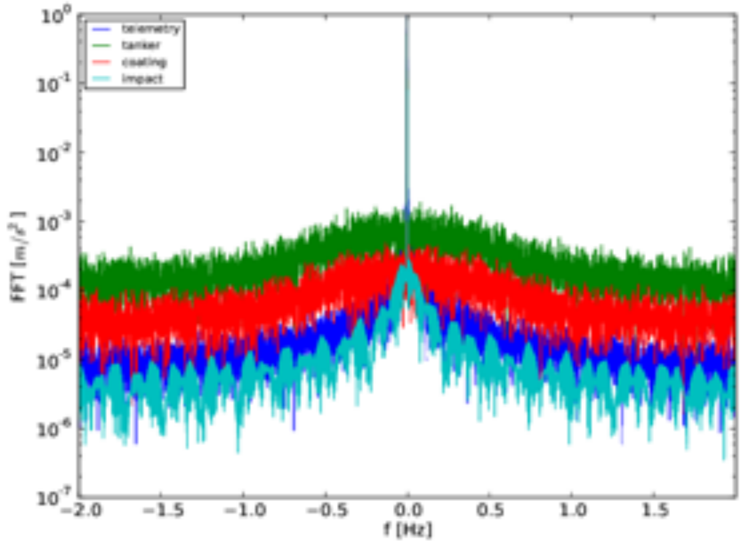


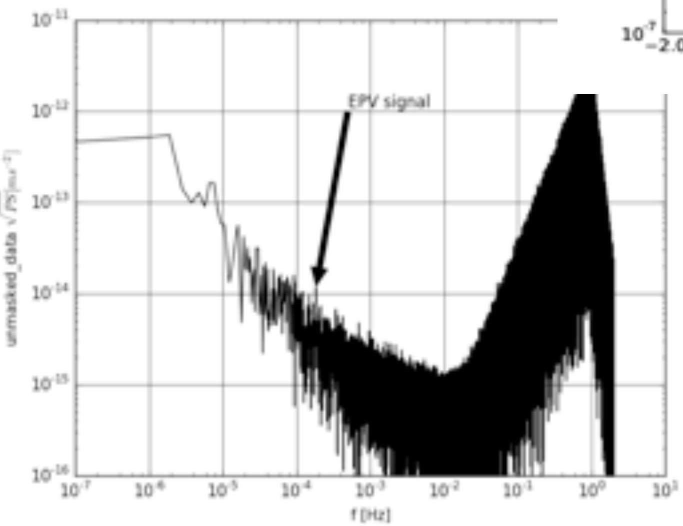
## Missing data

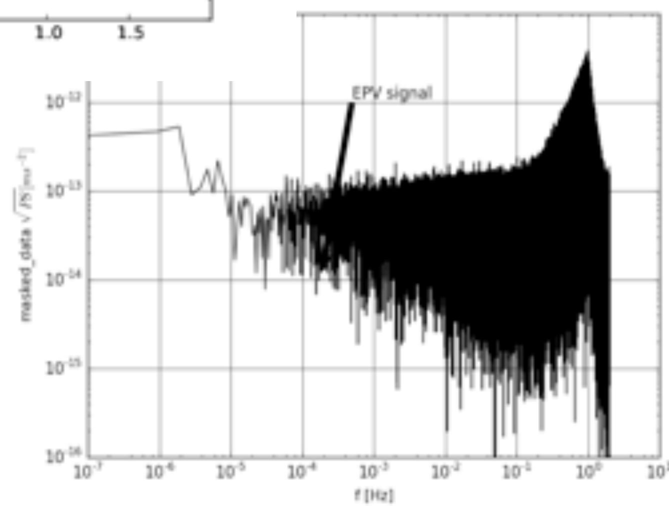
- **Teletransmission errors**
  - Information from Picard mission:
  - **frequency**: about 100 events over 10 months
  - **duration**: from seconds to hours
- **Coating cracking**
  - due to temperature changes (Earth / Space vacuum)
  - **frequency**: for each of the four satellite sides, about 6 times when the side faces the Earth
  - **duration**: 0.5-0.75s → 2 - 3 measurement points
- **Tank cracking**
  - worst case, depending on gas pressure
  - **frequency**: for each of the 6 tanks, about 43 times/orbit
  - **duration**: 0.5s → 2 measurement points

# Impact of missing data

Convolution of non-trivial spectral window with (signal+noise)'s power spectrum
=> **spectral leakage**



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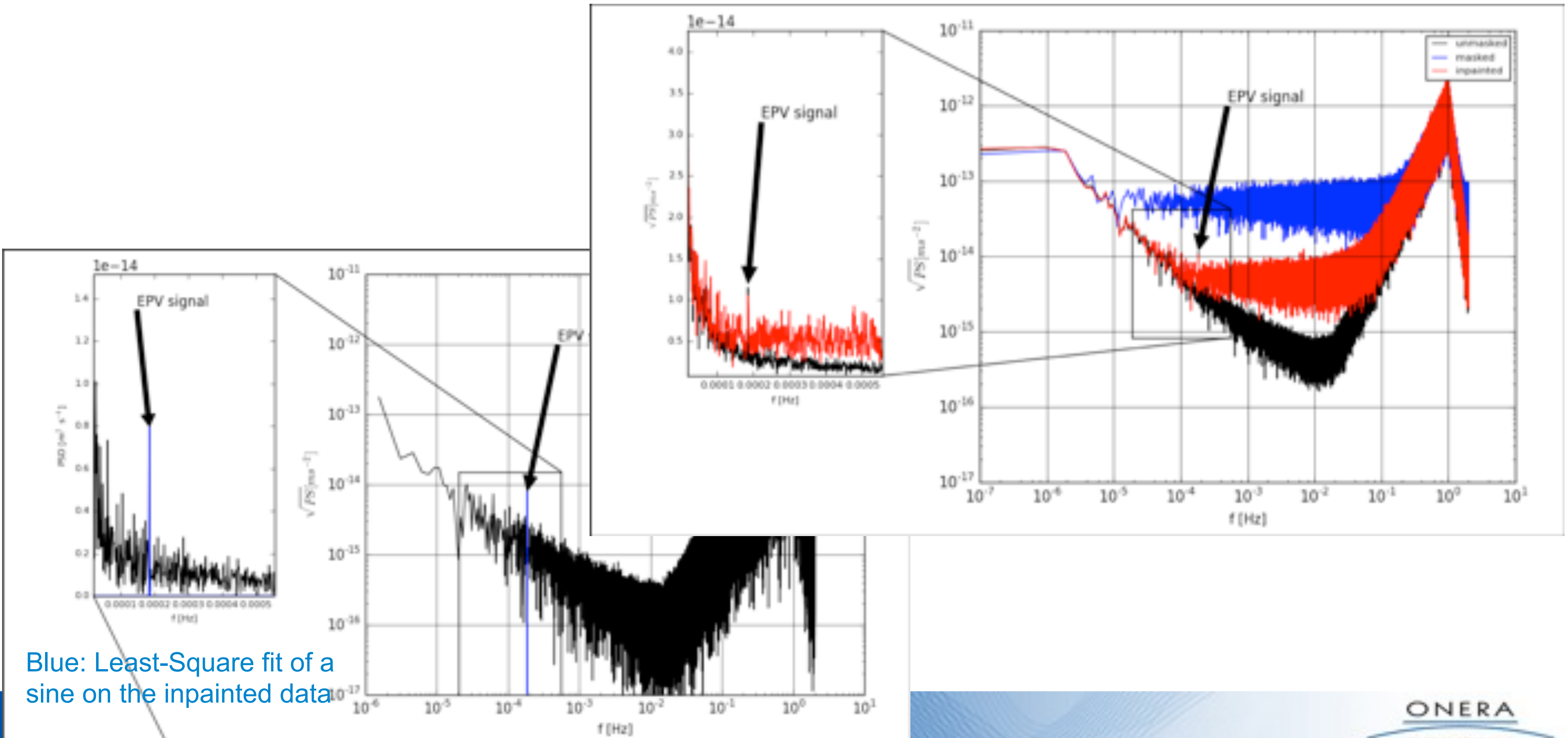
# Inpainting application to MICROSCOPE

- ✓ Inpainting developed by AIM/CEA, originally for 2D astronomy images; already adapted to time series for asteroseismology (J.L. Starck, S. Pires, S. Mathur's talks)
- ✓ Extrapolation of the missing information with sparsity prior on the solution: there is a function dictionary on which the complete data are sparse (very few non-negligible coefficients) but the incomplete data are not sparse




Blue: Least-Square fit of a sine on the inpainted data

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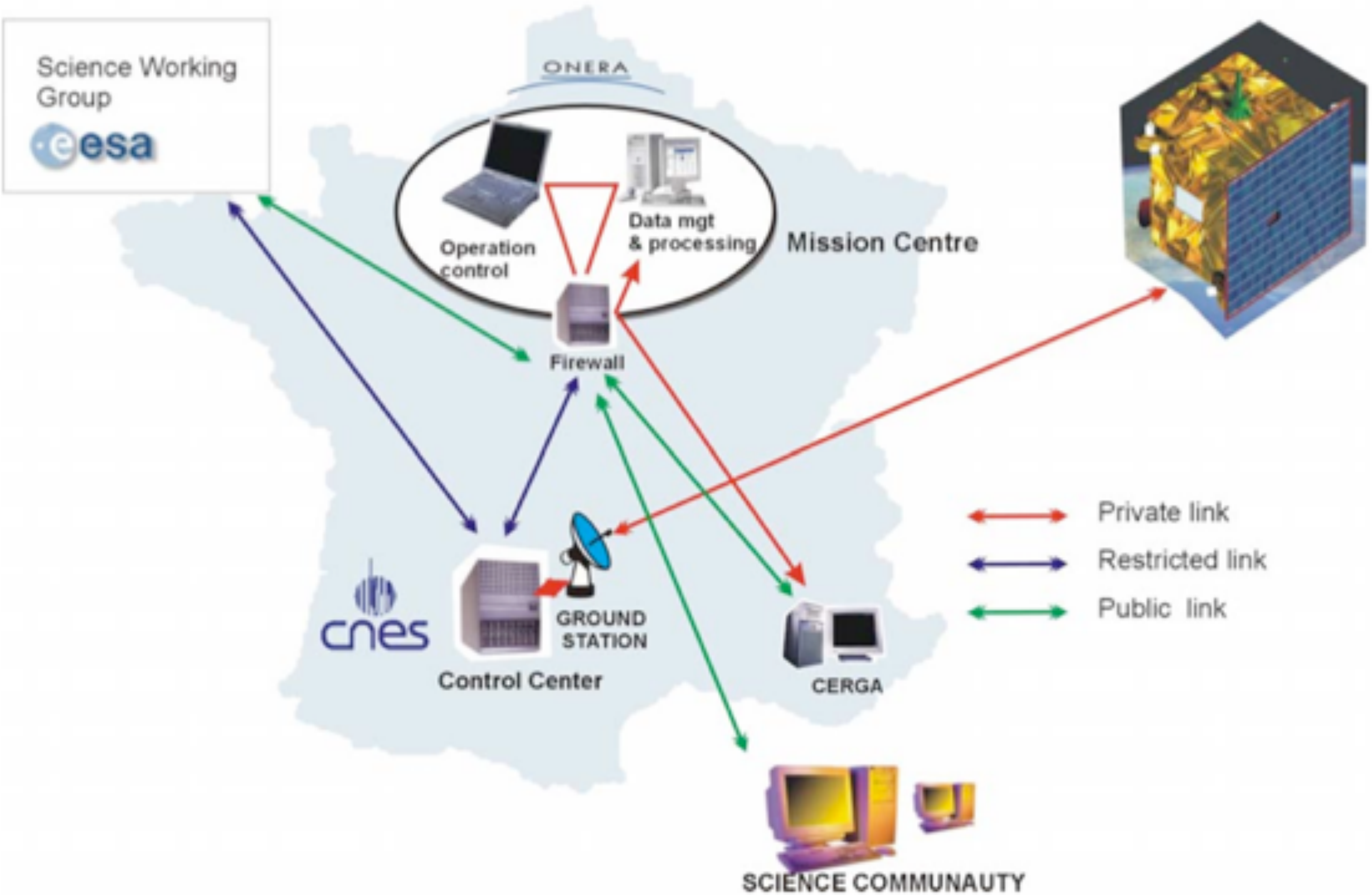
# MICROSCOPE ground segment



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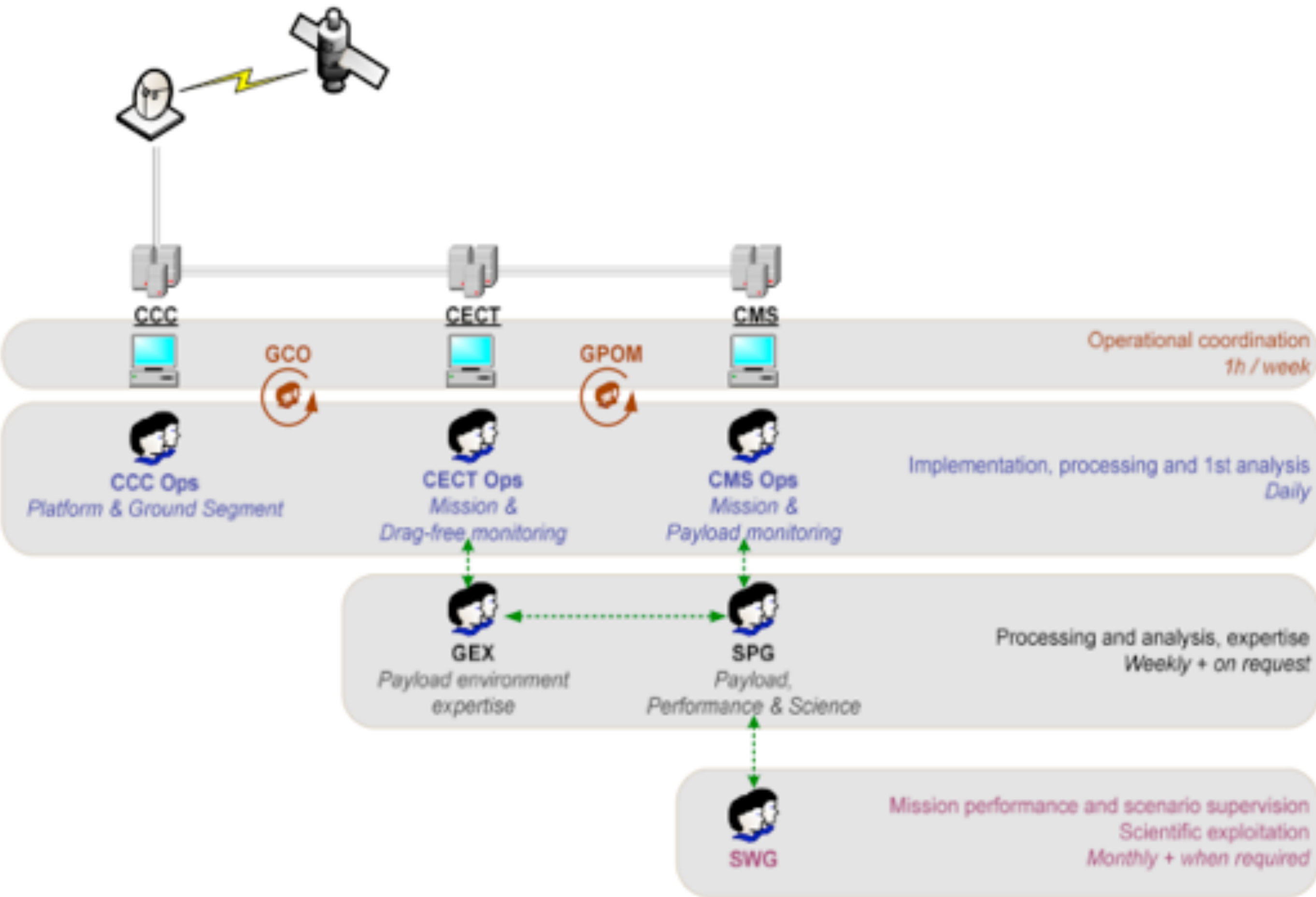
# Ground segment organization

**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



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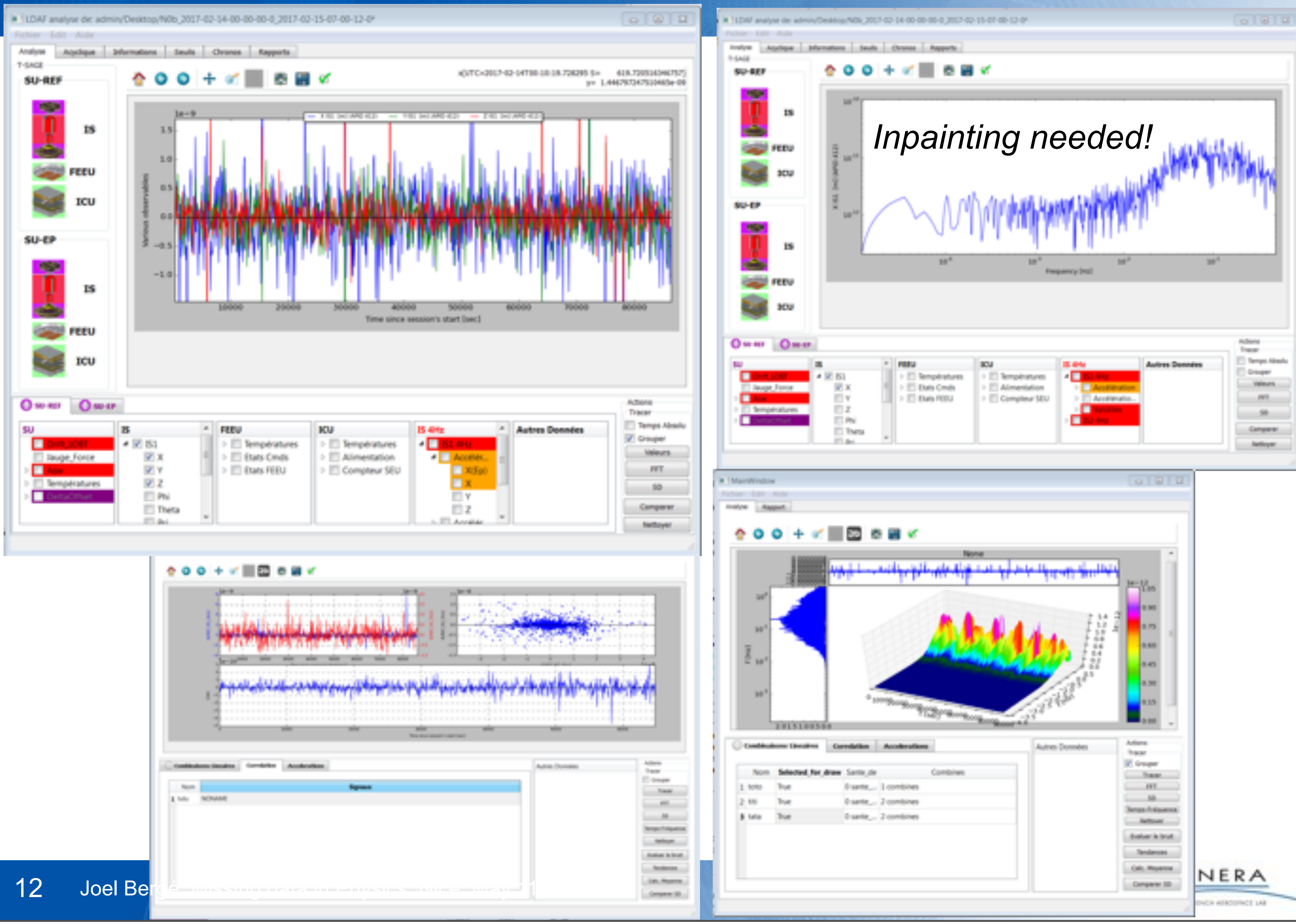
# MICROSCOPE Science Mission Center (CMSM)

- Ensure all operational functions to maximize instrument's operation
- Day-to-day instrument management and monitoring
- Weekly mission performance check
- Propose modifications to the mission scenario
- Data release and archiving

➔ **Different time scales with different flexibilities:**

- **1-week horizon: operational loop**
  - Verification of data integrity by automated processing
  - Mission program fixed (except potential stop or extension of a long session)
- **1-month horizon:**
  - Preliminary analysis of data
  - Scenario still modifiable, in the frame of the predefined sessions
- **1-year horizon:**
  - Detailed scientific analysis
  - Detailed performance analysis
  - Optimization of calibration processing
  - Application of data correction models

# Daily / Weekly operations: instrument monitoring



# Weekly / monthly: data analysis

★ Data architecture organization (see next slide)

★ Calibration: to go from raw data to usable data, usually on differential accelerations

- from on ground controls and models
- from in-flight assessments
- from in-flight dedicated sessions
- Most obvious calibrations: gravity gradient tensor
- Different levels of calibration

★ Treatment of invalid / missing data

- detection according to instrumental flags (provided in TMs) and/or thresholds crossings -> creation of a mask
- (optional) inpainting

★ Computation of differential accelerations (which are used to look for Equivalence Principle violation)

★ Search and estimation of the Equivalence Principle violation (Least-Square, KARMA -- see Q. Baghi's talks)

★ Data archiving and distribution

# MICROSCOPE data architecture: 3 levels

Operational
(Platform data, payload data, satellite orbit & attitude)

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: Pre-processed data (N0 x pre-defined calibration matrix)

b: Data corrected with as little "scientific bias" as possible

c: Best data (impacted by validity and calibration choices)

# Conclusion and prospects

★ MICROSCOPE data analysis is a complex task: look for and estimate a very weak signal in a colored-noise dominated time-series

★ Made much more difficult by missing data: leakage of high-frequency noise on frequencies where the signal is expected

★ Inpainting allows us to correct for missing data well enough to detect the signal

★ Inpainting will be used from day-to-day instrument's monitoring operations to scientific expertise and analysis

★ CMSM is responsible for the data processing, analysis, archiving and distribution

★ Different levels of data will be provided:

- ✦ Level 1 data (organized by inertial sensor) can be used to:
  - ✓ estimate Eötvös parameter from data weakly impacted by CMSM's validity and calibration choices
  - ✓ perform other applications (gravity, aeronomy...) not depending on differential mode
- ✦ Level 2 data (optimized for the differential mode)
  - ✓ include corrections
  - ✓ allow most direct estimation of the Eötvös parameter
- ✦ Auxiliary data: orbit, attitude...