Special experiments on LISA Pathfinder's Inertial Sensors

Status of thermal and electrostatic experiments

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Experiments to characterise stray force noise sources on the LPF test masses:

1) Thermal experiments on the Inertial Sensors
   - Residual gas effects
   - Temperature gradient effects

2) Electrostatic experiments
   - TM charge
   - Stray voltages

3) Magnetic experiments
   - TM susceptibility & remnant magnetic moment

Credits: Airbus Defence and Space
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Back to $\Delta g$: How about white noise?

- LPF first results: *PRL 116, 231101 (2016)*

White noise: is it *Brownian noise* from residual gas motion in the Inertial Sensors?

$$S_{\Delta g, Brw} = \frac{\rho (P_1 + P_2)}{m^2} s^2 \sqrt{\frac{512 m_0 k_B T}{\pi}} \left(1 + \frac{\pi}{8}\right)$$
The LTP Inertial Sensors

- Inertial Sensors placed inside Vacuum Enclosures
- Vacuum Enclosures sealed on ground before integration to satellite
- Opened to space since TM decaging once in L1 (2 Feb 2016)
- Since then, pressure expected to decay with $\frac{1}{(t-t_v)^p}$

$\rightarrow$ Typical **outgassing** decay for vented systems

$$Q(t, T) = \sum_{i=1}^{N} Q_{i0} e^{-\frac{\Theta_i}{T}} \frac{Q_{\text{eff}}}{(t-t_v)^p} e^{-\frac{\Theta_{\text{eff}}}{T}}$$

$$P(t, T) = \frac{Q(t, T)}{C_{\text{vent}}} = \frac{Q_{\text{eff}}}{C_{\text{vent}}} \frac{e^{-\frac{\Theta_{\text{eff}}}{T}}}{(t-t_v)^p}$$

$$S_{\Delta g, \text{Brw}} \approx \frac{S_{\text{eff}}}{(t-t_v)^p} e^{-\frac{\Theta_{\text{eff}}}{T}}$$
Brownian noise evidence (1)

- White noise roughly estimated by averaging $\Delta g$ PSD between 3-8 mHz
- Decaying with time as $\frac{1}{(t-t_v)^p}$ & strongly temperature dependent

PRELIMINARY!
Brownian noise evidence (2)

- Eventual “DC” pressure gradients across the masses could decay with same time constant.
- White noise decay correlated with $\Delta g$-DC → both caused by same outgassing sources?

→ Series of thermal experiments to estimate pressure via temperature gradient effects.

PRELIMINARY!
Temperature gradient effects in the Inertial Sensor

- Temperature gradients ($\Delta T$) induce net forces on the masses through different effects:
  
  $\rightarrow$ **Radiation pressure**: pressure exerted by electromagnetic radiation from the surfaces

  \[ F_{RP} = k_{RP} T^3 \Delta T \]

  $\rightarrow$ **Radiometric effect**: significant in rarefied atmospheres where the particle mean free path is longer than the characteristic size of the system, hence particles bounce directly between surfaces

  \[ F_{RM} = k_{RM} \frac{P}{T} \Delta T \]

  $\rightarrow$ **Asymmetric outgassing**: forces exerted by the fluxes of particles emitted from the surfaces

  \[ F_{OG} = k_{OG} \frac{\Theta_{eff} e^{-\Theta_{eff}/T}}{T^2} \Delta T \]

- Expected contributions (via simulations & on-ground tests, *Phys. Rev. D* 76, 102003)

\[
F = \left[ 23 \frac{pN}{K} \left( \frac{P}{10^{-5} \text{ Pa}} \right) \frac{293 \text{ K}}{T_0} + 9 \frac{pN}{K} \left( \frac{T_0}{293 \text{ K}} \right)^3 + 40 \frac{pN}{K} \left( \frac{Q_0}{1.4 \text{ nJ/s}} \right) \left( \frac{\Theta}{3 \times 10^4 \text{ K}} \right) \left( \frac{293 \text{ K}}{T_0} \right)^2 \right] \Delta T
\]

- Inertial Sensors equipped with heaters and sensors as part of Thermal Diagnostics Subsystem
Thermal diagnostics subsystem

- Temperature sensors: NTC thermistors with $10^{-5} \text{ K/sqrt(Hz)}$ sensitivity
- Heaters: able to apply custom signals for characterization purposes
- Also thermal items on the Optical Bench, Optical Window & Struts
ΔT Thermal experiments in flight

- Several temperature gradient experiments performed during the mission

\[ \Delta T_x = \frac{(T_3 + T_4) - (T_1 + T_2)}{2} \]

PRELIMINARY!
Thermal coefficients

- Thermal coefficient defined as $\alpha = \frac{F_{\text{mod}}}{\Delta T_{\text{mod}}}$
  - Couplings of $< 70 \text{ pN/K}$, time decay consistent with $\frac{1}{(t-t_0)^p}$
  - $\frac{d\alpha}{dT}$ also decaying with time due to outgassing decrease.
Brownian estimates [Preliminary]

- Estimated current pressure <5 μPa (at the beginning >20 μPa)
  - Assumed spices: water, activation energy of 8000-10000K
  - On-going analysis

\[ P \approx 5 \times 10^{-9} \text{ Pa} \text{ (at the beginning } >2 \times 10^{-7} \text{ Pa)} \]

Comment:
- Quite a good agreement
- Not perfectly overlapping, slightly underestimating the white noise level
- Need to improve the \( P \) estimation (currently working on corrections for the \( \frac{dF}{d\Delta T} \))

The recent change of temperature provides a good confirmation case.
Electrostatic experiments

- Main electrostatic interaction in the inertial sensors:

\[ F_x(q) = -\frac{q}{C_T} \left| \frac{\partial C_x}{\partial x} \right| \Delta x \]

- Two noise contributions

1. TM charge fluctuations \( S_q \) coupling with existing \( \Delta_x \)
   - Caused by high-energy cosmic rays and solar energetic particles

2. Stray voltage fluctuations \( S_{\Delta x} \) coupling with residual charge \( q \)
   - Caused by surface patch potentials and GRS electronics noise

- Experiments performed to estimate both contributions to LTP budget and minimise their impact.

- Main results to be published soon (arxiv:1702.04633)
Electrostatic experiments: charge estimate

- TM charge estimate by modulating voltage across the masses:

\[ q = \left[ \frac{C_T}{-4\left| \frac{\partial C}{\partial x} \right|} \right] \frac{F_{\text{mod}}}{V_{\text{mod}}} \]

- Measurements performed at both masses simultaneously by using different \( f_{\text{mod}} \)

- Net charge increments of +22.9e/s (TM1) and +24.5e/s TM2 (control by means of UV lamps)

- PSD \( \sim 1/f^2 \) & absence of correlation in the charge time-series of the 2 TMS: consistent with the model of independent Poissonian processes

- Noise stationary over months
Residual stray voltages across the masses ($\Delta_x$) are calculated by estimating slope $\frac{\partial F}{\partial q}$.

- Measured residual stray voltages of $\Delta_x \sim 20\text{mV}$ (TM1) and $<1\text{mV}$ (TM2).
- Small variation along 1 year of operations.
- Easily compensated to $\sim 1\text{mV}$.
Overview

- White noise on LTP central sensitivity noise curve is associated to Brownian motion of the residual gas inside the Inertial Sensors
- Temperature gradient modulation experiments allow to estimate pressure inside the Inertial Sensors
- Dedicated charge and stray voltage experiments allow to characterise noise contribution from random charge and stray voltages and to minimise their impact to the noise budget
- More experiments still going on...
Thanks for your attention
Bibliography


http://journals.aps.org/prd/abstract/10.1103/PhysRevD.76.102003