The Engineering of LISA Pathfinder – the quietest Laboratory ever flown in Space

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The Engineering of LISA Pathfinder – the quietest Laboratory ever flown in Space

Overview:

- Suppression of disturbances on-board the LISA Pathfinder “lab”:
  - Gravitational
  - Accelerations
  - Test Mass Charge
  - Thermal
  - Magnetic

- For each case:
  - Engineering Approach
  - Predicted vs In-flight Performance
  - Implications for LISA

Selected topics presented from an “industrial” perspective

Airbus DS (UK & Germany)
Gravitational Environment (I)

- Main gravitational parameters to be controlled:
  - DC differential and absolute accelerations (linear and angular)
  - Gravitational stiffness
  - AC accelerations

- Engineering approach:
  - Spacecraft design – eg no moving components, material choice
  - Verification by analysis (modelling) based on measured inputs
  - Strict gravitational control throughout manufacture – eg $O(10^4)$ mass measurements
  - Final mass balancing of residual imbalance
**Gravitational Environment (II)**

- Predicted vs In-flight performance*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pre-flight Estimate</th>
<th>In-flight Measurement</th>
<th>Requirement</th>
<th>Requirement Met</th>
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<tr>
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<td>(1.4±5.0)e-10 (TM1)</td>
<td>&lt;1.0e-8</td>
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<tr>
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<td>(-3.9±2.2)e-10 (TM2)</td>
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<td>-1.3e-9 (TM2)</td>
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<tr>
<td></td>
<td>-0.2e-9</td>
<td>-0.1e-9 (TM2)</td>
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</tbody>
</table>

*Absolute acceleration in Z parallel to Solar Radiation Pressure – dedicated experiment required to disentangle contributions*
Gravitational Environment (III)

- Effect of cold gas depletion (total mass 9.6kg) is well understood:

Slope change as a result of Feed Branch swap:
- Fit “by eye” $6.2 \times 10^{-13} \text{ms}^{-2}/\text{day}$.
- Gravitational prediction $6.6 \times 10^{-13} \text{ms}^{-2}/\text{day}$

- Selective propellant depletion is currently being used to control gravitational environment

Agreement to <10%
Gravitational Environment (IV)

- Pre-flight estimated contribution to acceleration noise **not** realised
  -> dAx significantly better than expected

- Implications for LISA:
  - No improvements to approach necessary
  - Effect of cold gas propellant depletion is understood and manageable – if adopted for LISA

- Considerations and improvements:
  - Moving parts (e.g., periodic High Gain Antenna re-pointing) will need assessment
  - (Partial) verification of gravitational requirements by test could result in time & cost savings, and reduce risks
Accelerations (I)

- Spacecraft (SC) shields Test Masses (TMs) from external disturbances
- Now relative SC – TM motion has to be minimised in order to reduce residual SC – TM couplings
- Engineering approach:
  - Drag-free Attitude Control System (DFACS) – a set of algorithms that controls both TMs and SC in 15DOFs (!)
    - Relies on low-noise sensors & actuators
    - Robust control from initial TM release to Science Mode
Accelerations (II)

- In-flight performance:
  - Initial conditions in orbit much worse than predicted
    - Initial offsets / velocities exceeded by factor up to 60 / 8
  - DFACS was nevertheless robust enough to capture the TMs
  - Transitions to science mode very robust and repeatable
  - Science mode performance better than predicted:
    - Sensor & actuator noise models conservative
    - Offsets and misalignments conservative
Accelerations (III)

- In-flight performance:
  - Relative SC/TM motion can be taken as proxy for residual SC accelerations – imagine that TMs are “perfect” free-fall reference
  - At low frequencies: SC motion many orders of magnitude quieter than Earth surface motion (seismic noise)
Accelerations (IV)

- Implications for LISA:
  - DFACS science mode performance goes a long way towards LISA requirements
  - DFACS performance model has been verified and can be extended for LISA
  - Robustness of mode transitions could be improved further:
    - Uni-directional thruster configuration efficient but limits authority in critical phases. Additional thrusters would enhance margins
    - Margins for suspension actuation should be increased → would account for disturbance uncertainties
  - Excellent low frequency TM isolation – one of the (two) main reasons for going to space!
Test Mass Charge (I)

- Net electrostatic charge on Test Masses (e.g., from cosmic rays) results in unwanted SC – TM interactions → needs to be controlled

- Engineering approach:
  - Charge Management System (CMS):
    - Provides a robust way to reduce unwanted charges on the Test Masses
    - Automatic on-board algorithms to achieve regular discharging without much ground interaction
Test Mass Charge (II)

- Predicted vs In-flight Discharging Performance
  - On-board charge estimation performance in line with pre launch predictions
  - Closed loop discharge control performance also in line with predictions
  - On-board closed loop fast discharge now used regularly for LTP and DRS operations
Test Mass Charge (III)

- Implications for LISA
  - On-board charge estimation has been verified for LISA
    - Very flexible and can be adjusted for the use of different degrees of freedom
    - If possible, optical readout should be used
  - Principle of closed loop discharge control has been verified
  - Robustness of closed loop discharge control could potentially be improved → e.g. optimization of light injection to avoid need for DC biasing
  - Review UV harness installation QA (!)
Thermal Environment (I)

- Thermal stability at low frequency is essential to realise required noise performance
- Engineering approach:
  - L1 orbit – very stable environment
  - Nested SC design – main features:
    - No unit or heater switching during nominal operations
    - Purely passive thermal control (heaters ON or OFF)
    - Extensive thermal test campaigns
Thermal Environment (II)

- In-flight performance
  - Solar Array: very slow drift due to increasing Sun distance
  - LCA Cage: $\approx 10^{-3} \text{K/\sqrt{Hz}}$ at 1mHz
  - Optical Bench: $\leq 3 \times 10^{-5} \text{K/\sqrt{Hz}}$ down to 0.1mHz

\[ \Delta T/\Delta t = -0.4 \text{K/6days} \]
Thermal Environment (III)

- Implications for LISA
  - Stable external environment helps – LISA will also benefit from this
  - Solar Array shadowing of spacecraft body essential for thermal stability
- Considerations and potential improvements:
  - “Nested” LPF spacecraft design helps – LISA will have large telescope apertures
  - Combination of (fixed) trim heaters is not as flexible as desired. Quiet PID control is possible.
  - Do not place PCDU near thermally most sensitive equipment (!)
Magnetic Environment (I)

- Non-zero magnetic TM properties couple to local magnetic environment generating acceleration noise. Need to control:
  - DC field and field gradients
  - Fluctuating fields and field gradients
- Approach:
  - By design – avoid magnetic parts / EMC design guidelines
  - Unusual frequency range – extensive test campaign at unit and spacecraft level
Magnetic Environment (II)

- Predicted vs In-flight performance
  - Local DC fields of order 1µT as predicted
  - Low frequency field fluctuations are uniform across SC – can be attributed to Sun.

\[ x \sqrt{2}/0.8 \text{m} \]

\[ \approx 30 \text{nT/Hz} @ 1\text{mHz} \]

\[ \approx 20 \text{nT/m/Hz} @ 1\text{mHz} \]
Magnetic Environment (III)

- Pre-flight estimated contribution to acceleration noise **not** realised
  → Local DC gradient estimate was dominated by measurement uncertainty!

- Implications for LISA
  - No showstoppers / real problems identified
  - The following should be improved:
    - DC magnetic gradient testing (in particular for payload elements in close proximity)
    - Low frequency behaviour of high frequency AC lines should be characterised
  - New equipment (eg TWTA) still needs to be characterised
Summary / Conclusions

- LISA Pathfinder as a laboratory has been demonstrated to be:
  - Well controlled and understood from a gravitational point of view
  - Exceptionally quiet as far as residual accelerations are concerned
  - Extremely quiet from a thermal point of view
  - Sufficiently quiet from a magnetic point of view

- The above has been achieved thanks to a combination of:
  - orbit choice around L1
  - clever Payload & Spacecraft design
  - excellent communication within the whole collaboration
  - a bit of luck 😊

- No problems identified for LISA – although a few details could be improved

*We are ready to go and keen to start building LISA!*
Thank you!