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

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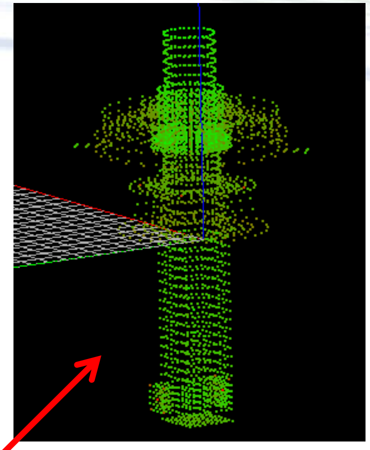
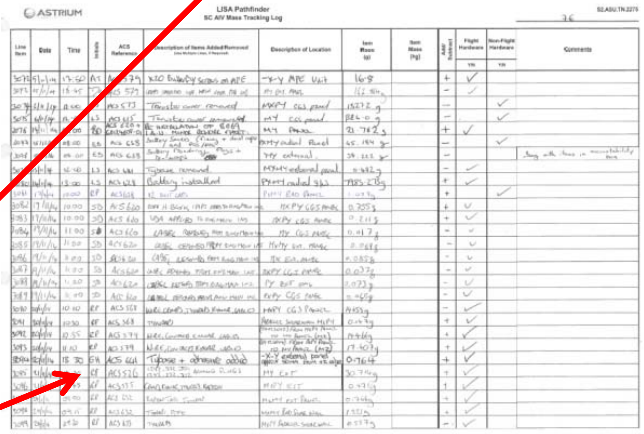
Gravitational Environment (I)

- 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



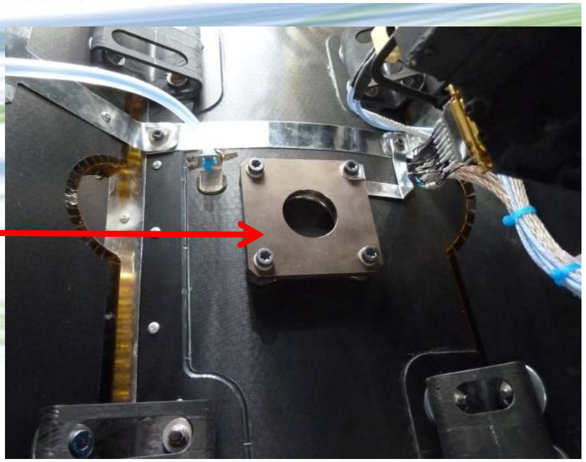


ASTRIUM

LISA Pathfinder
SC AIV Mass Tracking Log

S2.ASU.TN.2275

Line Item	Date	Time	Initials	ACS Reference	Description of Items Added/Removed (Use Multiple Lines, if Required)	Description of Location	Item Mass (g)	Item Mass (kg)	Add/Subtract	Flight Hardware Y/N	Non-Flight Hardware Y/N	Comments



Gravitational Environment (II)

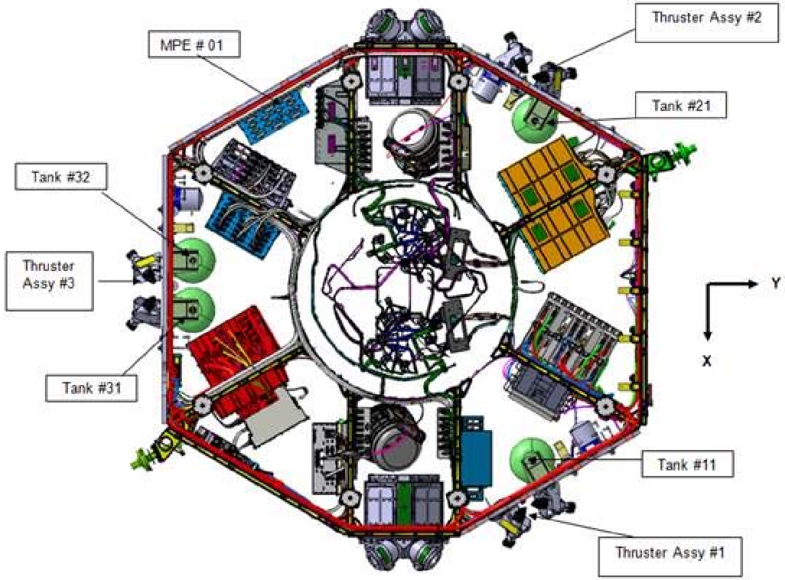
- Predicted vs In-flight performance*

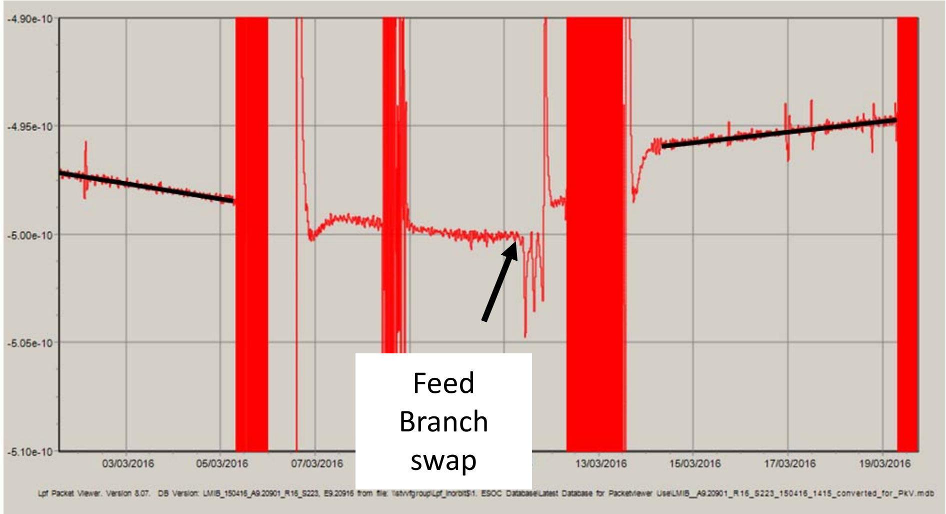
Parameter	Pre-flight Estimate	In-flight Measurement	Requirement	Requirement Met
Ax	-1.7e-10 -1.8e-10	(1.4±5.0)e-10 (TM1) (-3.9±2.2)e-10 (TM2)	<1.0e-8	Yes
Ay	-1.5e-9 -1.5e-9	(-1.0±0.2)e-9 (TM1) (-1.9±0.2)e-9 (TM2)	<1.0e-8	Yes
dAx	<5.5e-10	<1.0e-10	<6.5e-10	Yes
dAy	<3.9e-10	5.0e-10	<1.1e-9	Yes
dAz	<2.8e-10	0.1e-10	<1.85e-9	Yes
θ	-0.4e-9 +0.4e-9	-0.6e-9 (TM1) -0.1e-9 (TM2)	<13.5e-9	Yes
η	+3.1e-9 -1.2e-9	+2.9e-9 (TM1) -1.3e-9 (TM2)	<11.5e-9	Yes
ϕ	+0.8e-9 -0.2e-9	+1.0e-9 (TM1) -0.1e-9 (TM2)	<8.0e-9	Yes

*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:





Feed Branch swap

Slope change as a result of Feed Branch swap:

- Fit “by eye” 6.2x10^{-13}ms^{-2}/day.
- Gravitational prediction 6.6x10^{-13}ms^{-2}/day

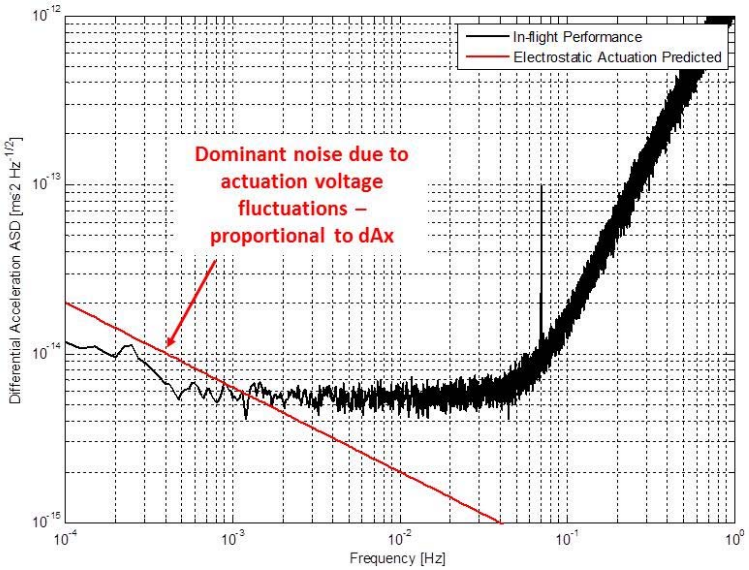
Agreement to <10%

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

Gravitational Environment (IV)

- Pre-flight estimated contribution to acceleration noise **not** realised

→ dAx significantly better than expected

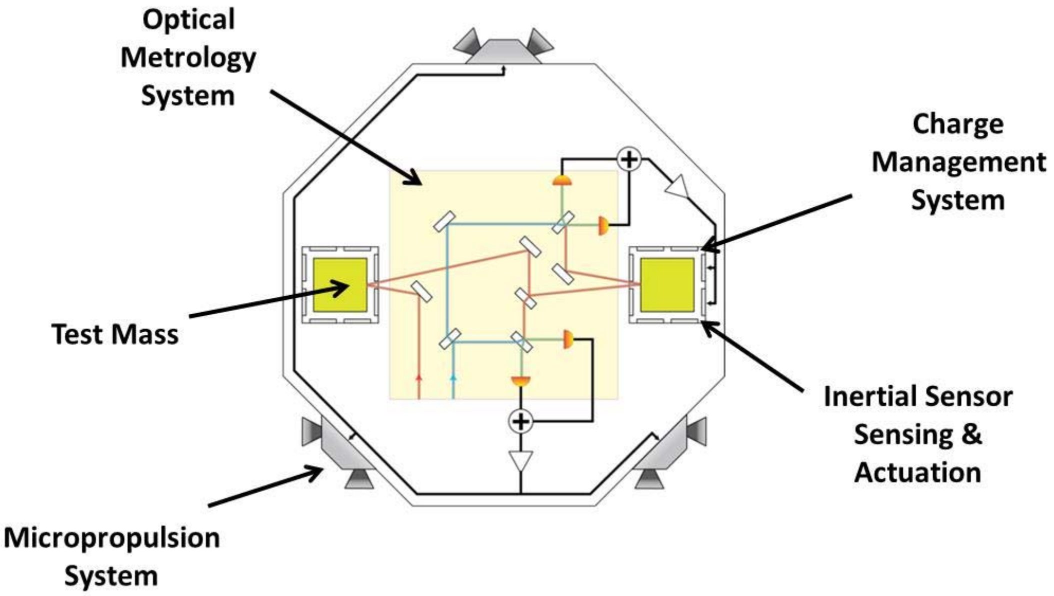


Dominant noise due to actuation voltage fluctuations – proportional to dAx

- 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 (eg 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

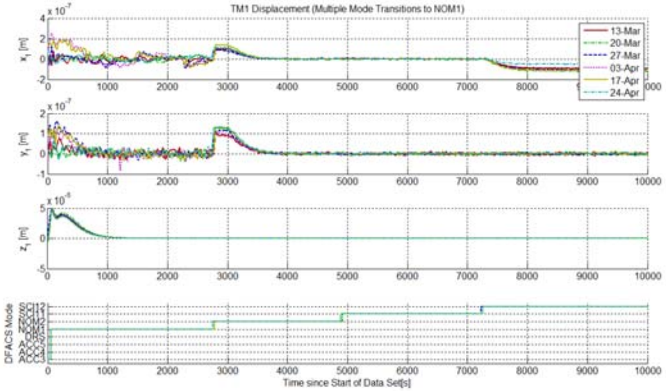
Accelerations (I)

- 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

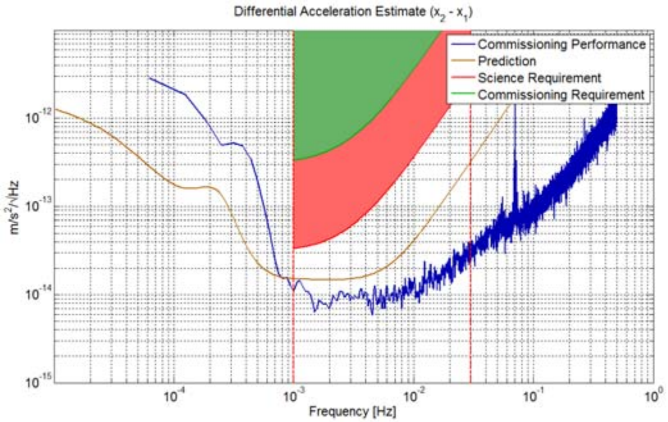


Accelerations (II)

- 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



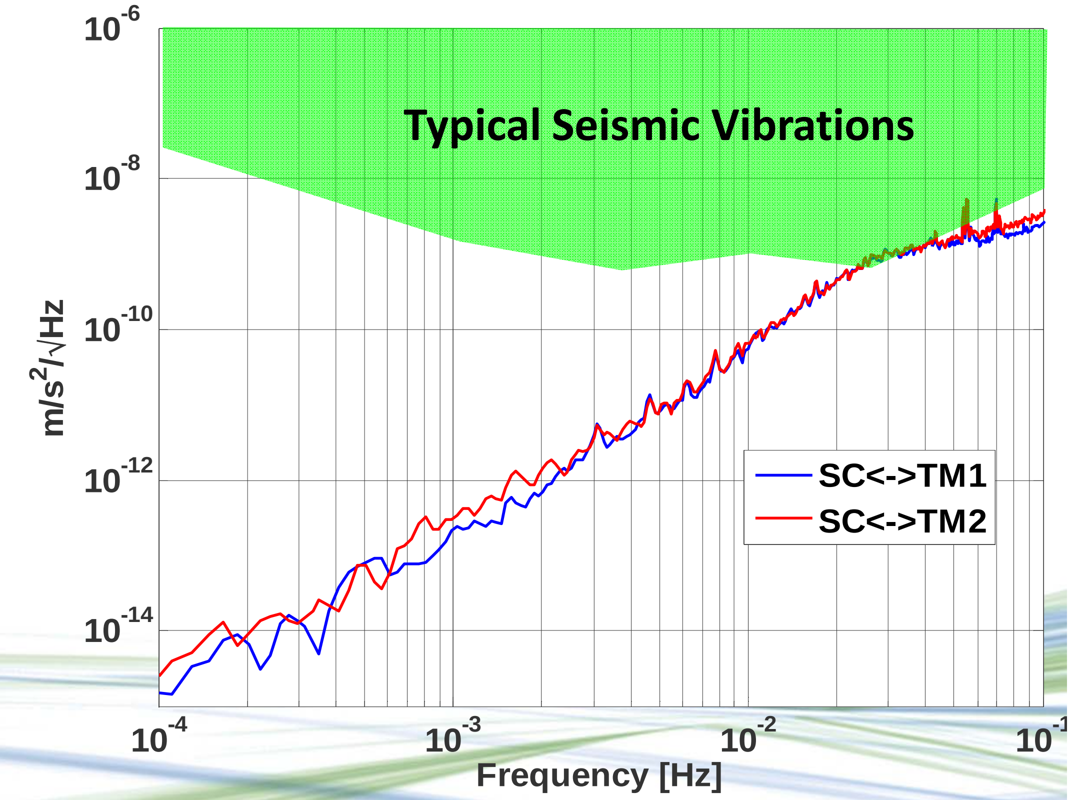
Set of Mode Transitions from ACC3 to SCI12



SCI12 Performance during Commissioning

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)

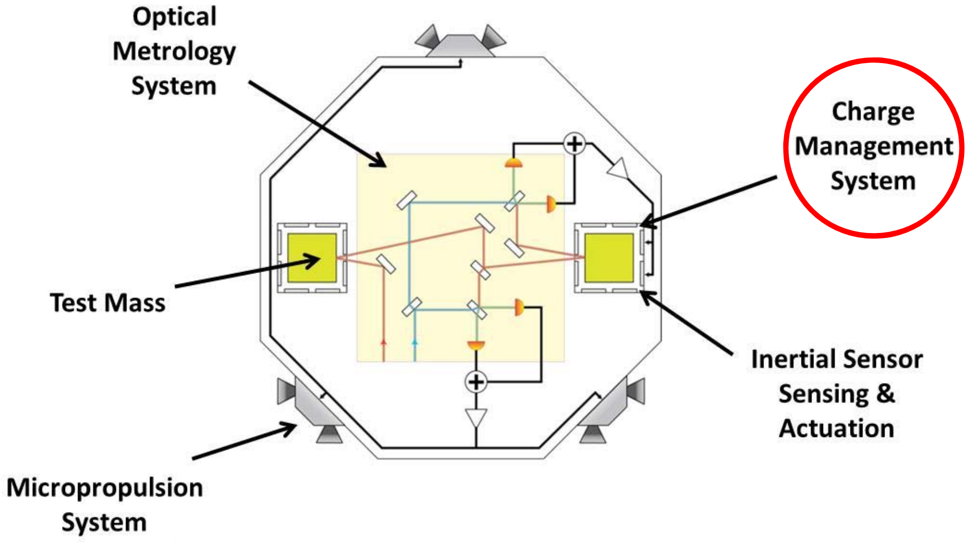


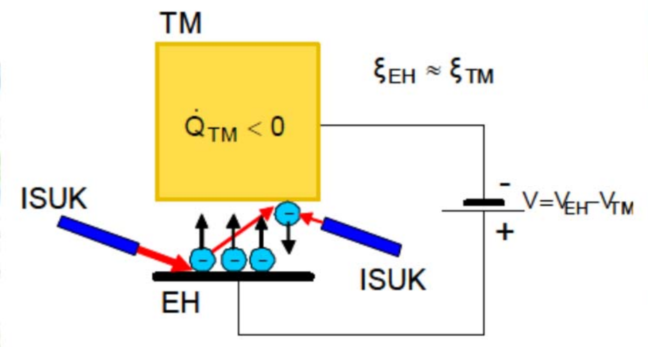
Accelerations (IV)

- 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)

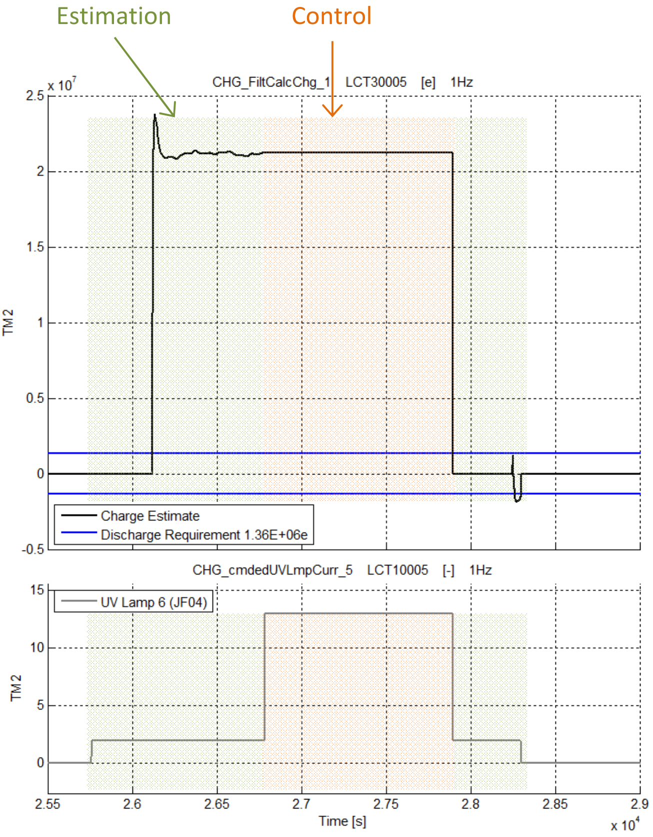
- Net electrostatic charge on Test Masses (eg from cosmic rays) results in unwanted SC – TM interactions → needs to be controlled
- Engineering approach:
  - Charge Management System (CMS):
    - Provides a robust way to reduce unwanted charges on the Test Masses
    - Automatic on-board algorithms to 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



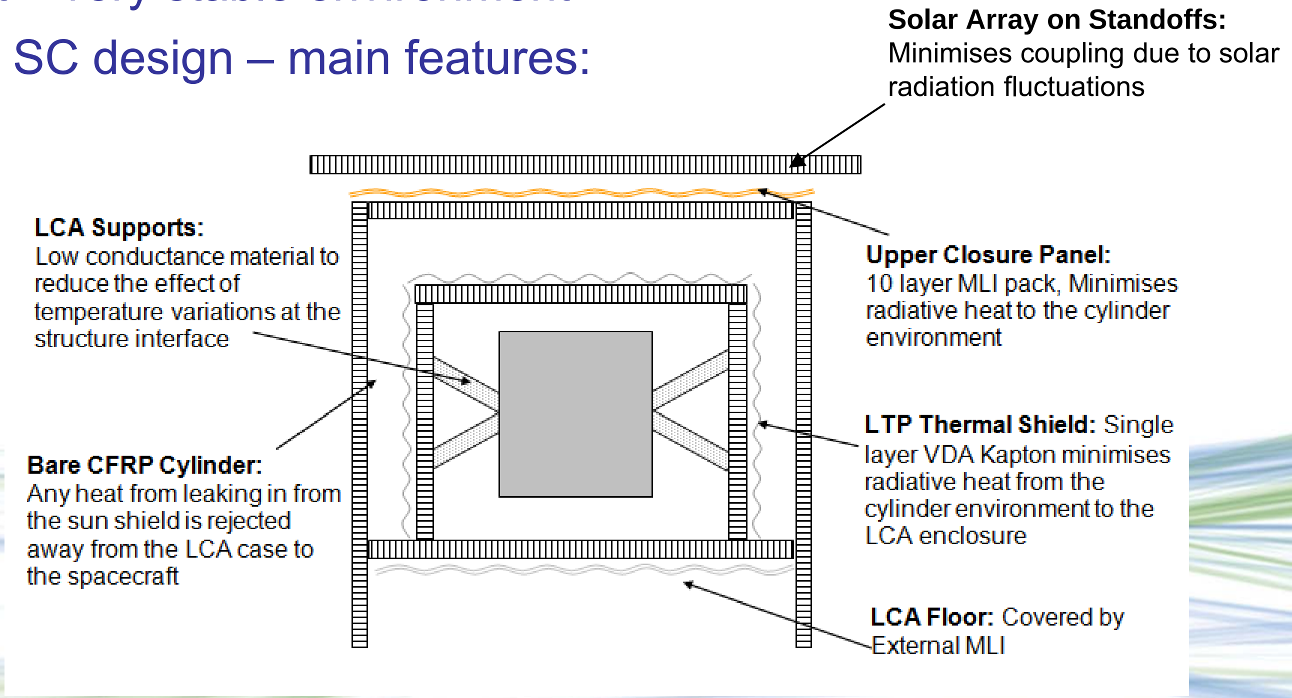
TM2 Closed Loop Discharge Performance

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:



Solar Array on Standoffs: Minimises coupling due to solar radiation fluctuations

LCA Supports: Low conductance material to reduce the effect of temperature variations at the structure interface

Upper Closure Panel: 10 layer MLI pack, Minimises radiative heat to the cylinder environment

LTP Thermal Shield: Single layer VDA Kapton minimises radiative heat from the cylinder environment to the LCA enclosure

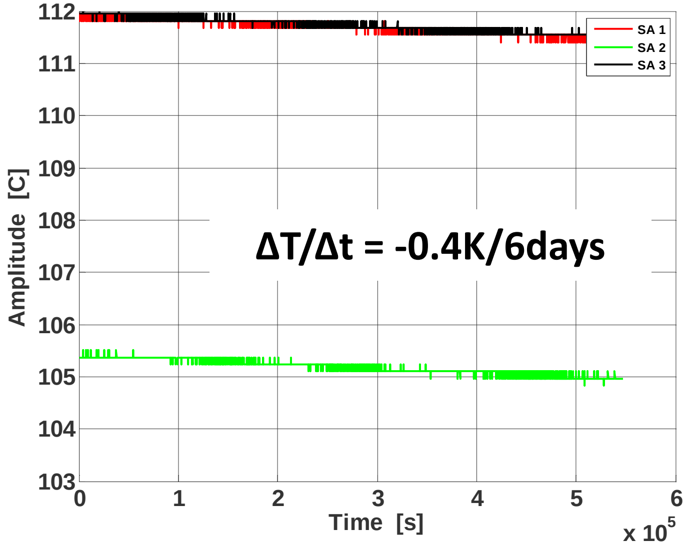
Bare CFRP Cylinder: Any heat from leaking in from the sun shield is rejected away from the LCA case to the spacecraft

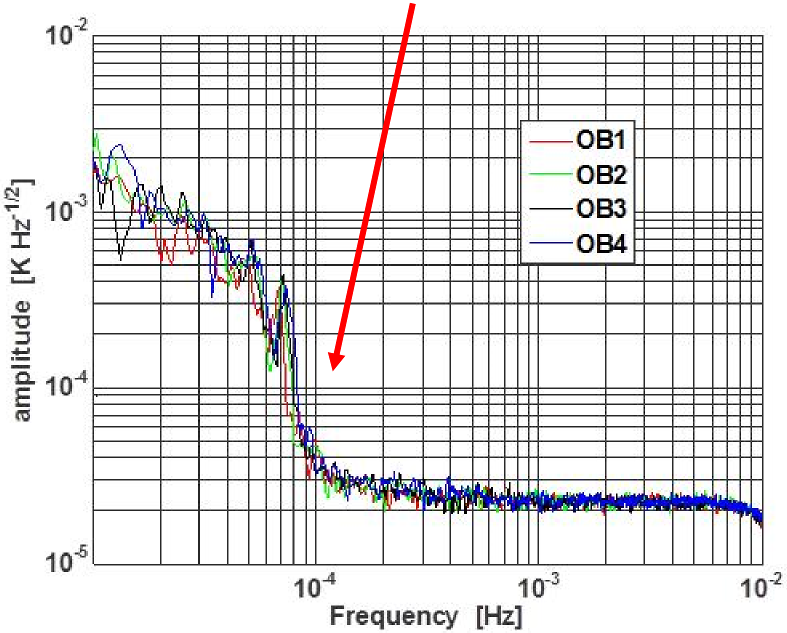
LCA Floor: Covered by External MLI

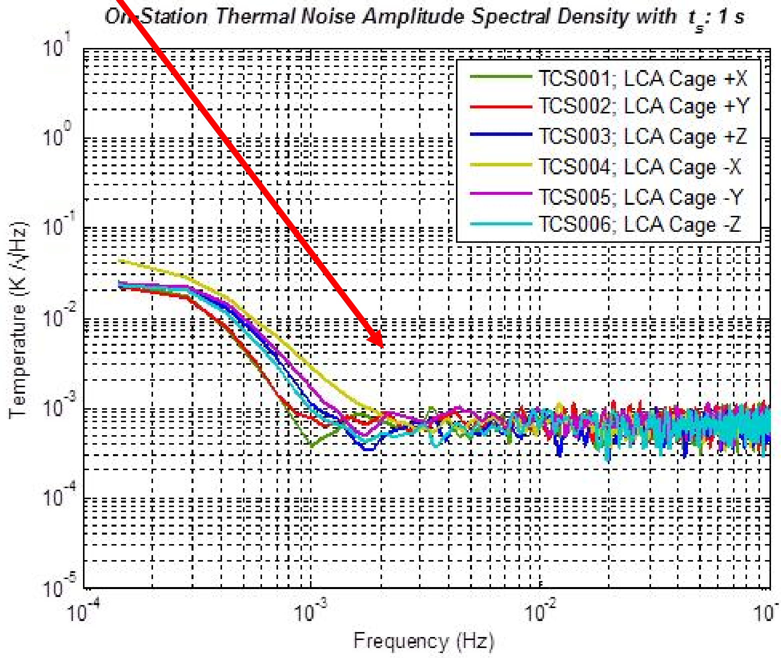
    - No unit or heater switching during nominal operations
    - Purely passive thermal control (heaters ON or OFF)
    - Extensive thermal test campaigns

Thermal Environment (II)

- In-flight performance
  - Solar Array: very slow drift due to increasing Sun distance
  - LCA Cage: ≈10^{-3}K/√Hz at 1mHz
  - Optical Bench: ≤3×10^{-5}K/√Hz down to 0.1mHz


ΔT/Δt = -0.4K/6days





Thermal Environment (III)

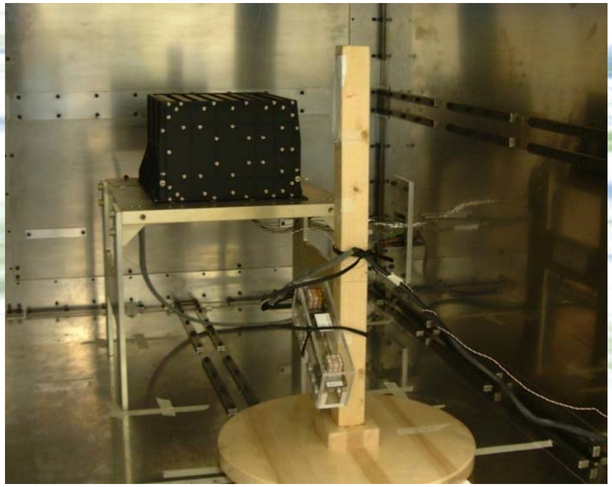
- Implications for LISA
  - Stable external environment helps – LISA will also benefit from this
  - Solar Array shadowing of spacecraft body essential for thermal stability
  - Considerations and potential improvements:
    - “Nested” LPF spacecraft design helps – LISA will have large telescope apertures
    - 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

LPF SC at IABG

IS FEE SAU



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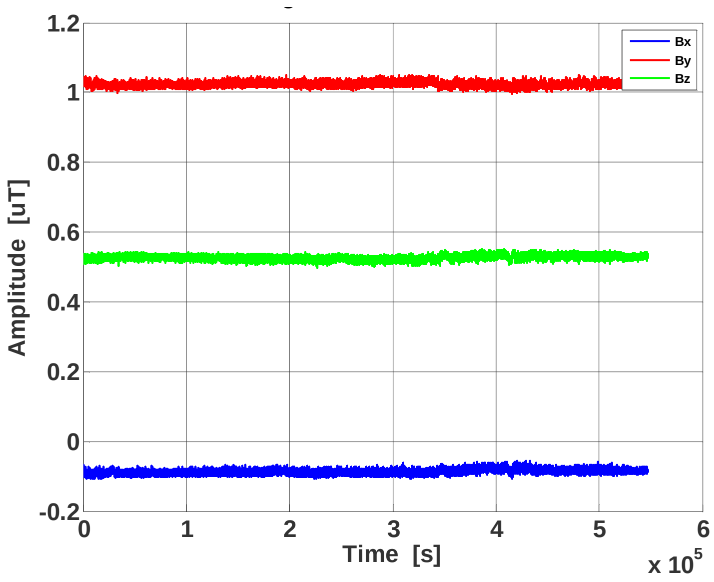
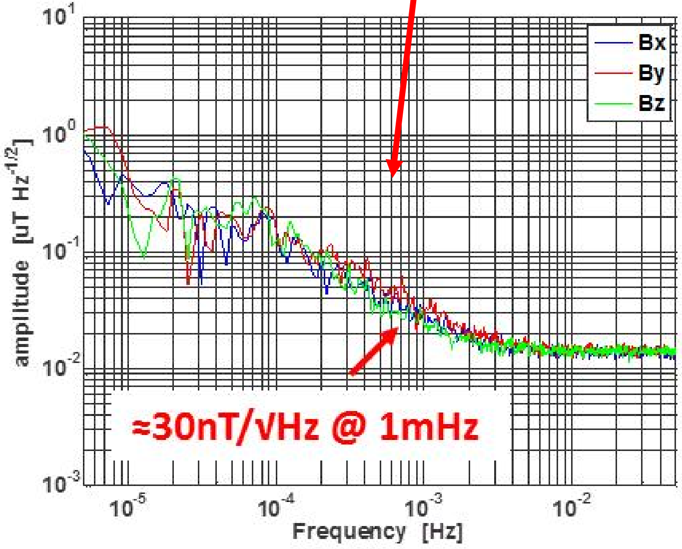
Magnetic Environment (II)

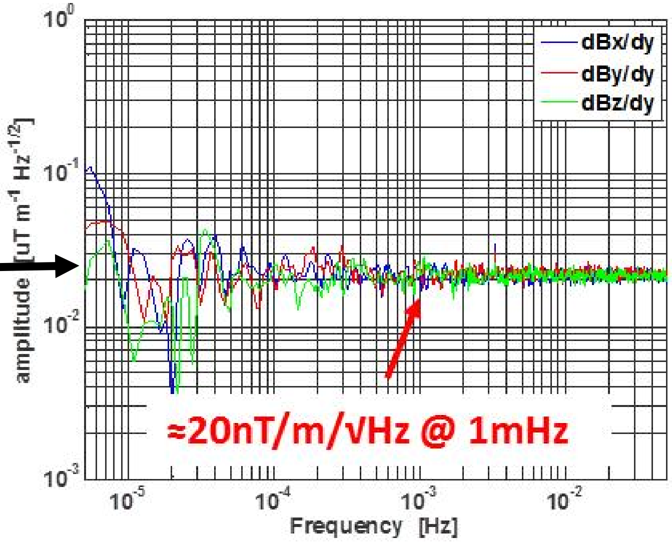
- Predicted vs In-flight performance
  - Local DC fields of order 1μT as predicted
  - Low frequency field fluctuations are uniform across SC – can be attributed to Sun.





≈30nT/√Hz @ 1mHz

x √2/0.8m

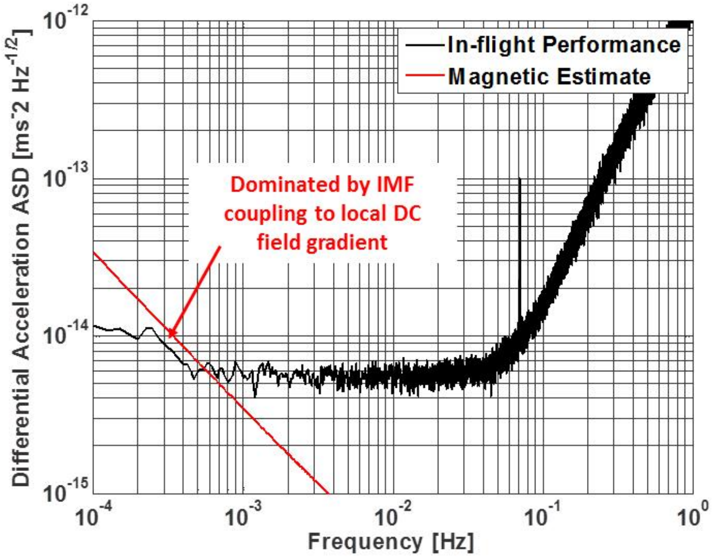


≈20nT/m/√Hz @ 1mHz

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!

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- Albert Einstein Institute
- University of Glasgow
- University of Birmingham
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