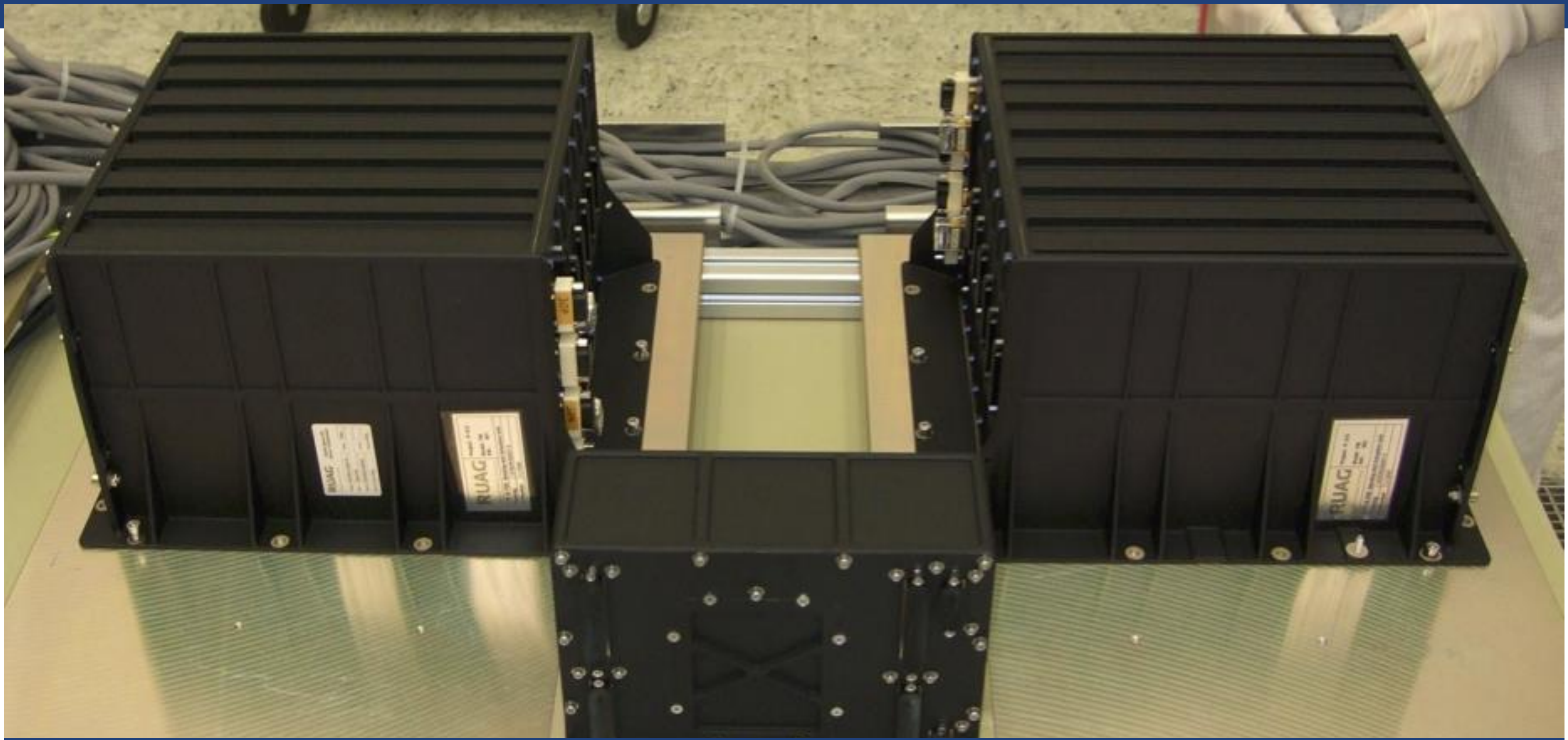
ETH zürich



From IS FEE to GRS FEE
LPF IS FEE Performances and Operations

Luigi Ferraioli

Outline

- The IS FEE for LPF
  - Function and working principle
  - History and development
  - Operations and performances
- The route to LISA
  - GRS FEE new development new challenges

IS FEE Functions Specifications

Unit Purpose

IS FEE
Electronic Unit to enable the functions of the IS/GRS

Subsystem level Functions

IS FEE
Main Functions

Sensing
Enabling the capacitive sensing of the TM

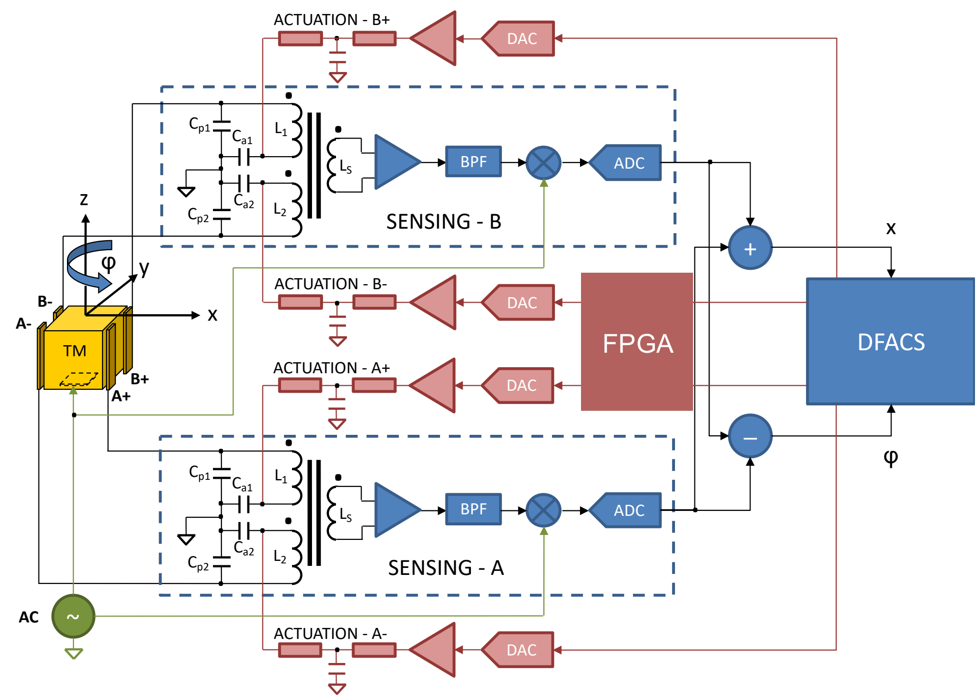
Actuation
Enabling control of the TM

Unit level Functions

- TM Sensing
- TM bias
- TM Actuation
- Command and Data Interface
- HK Interface
- Interface with Power

IS FEE Working principle

- Actuation scheme based on digital waveform synthesis and sigma delta digital to analog conversion. Actuation waveform at audio frequency (60 – 300 Hz) to provide effective DC forces at the TM
- Sensing scheme: Differential capacitance sensed by the transformer bridge working at resonance, transimpedance amplification, carrier demodulation and analog to digital conversion. The motion of the TM provides an amplitude modulation on the carrier at 100 kHz, which is them demodulated in the FEE.
- Position sensing of TM, up to 200 μm with nm precision
- Actuation Control TM with effective DC actuation forces of ~nN with fN precision



IS FEE Functions Requirements

Science Mode - Sensing
Position sensing of TM, up to 200 μm

Science Mode - Actuation
Control TM with effective DC actuation forces of ~nN

Non-Science Mode - Sensing
Position sensing of TM, up to 2.5 mm

Non-Science Mode - Actuation
Control TM with effective DC actuation forces of ~μN

Unit Operating Modes

- High Resolution Mode
- Wide Range Mode

LPF IS FEE Some History

Switzerland enters in the LPF consortium to develop the IS FEE 2003

↓

ETH Zurich is the IS FEE PI and develop the first prototypes (2003 - 2005)

↓

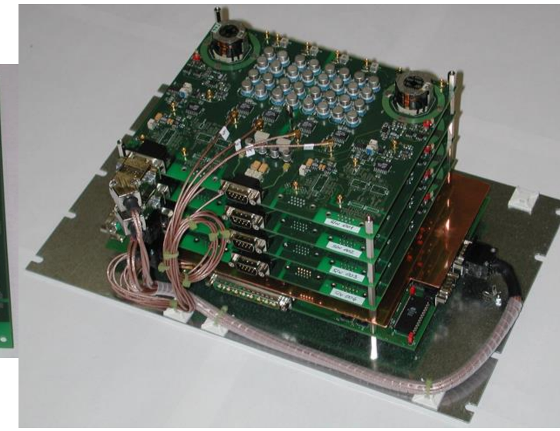
TAS-CH (Contraves / RUAG) and HESSO are selected for the industrial development - 2005

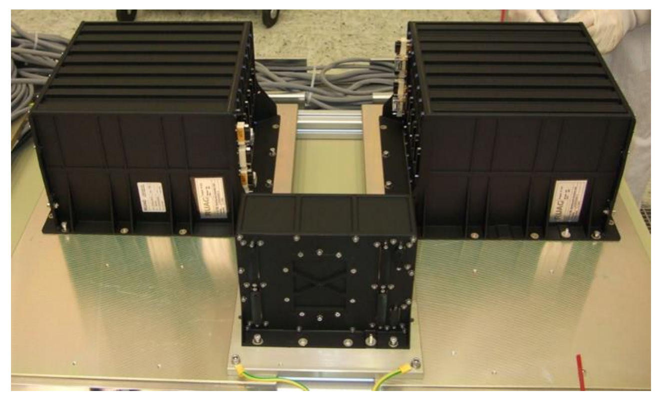
↓

IS FEE is delivered in 2009

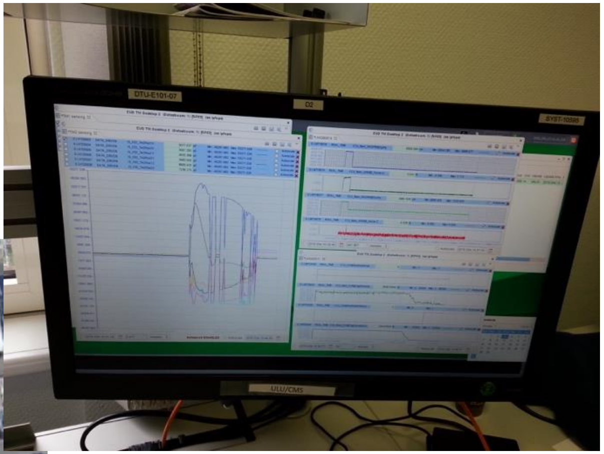
↓

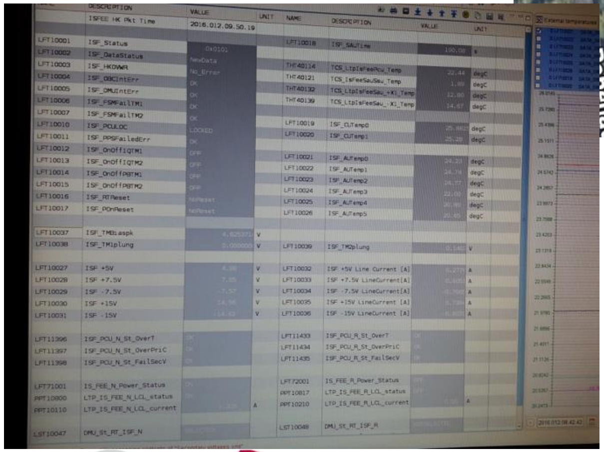
LPF Launch in 2015

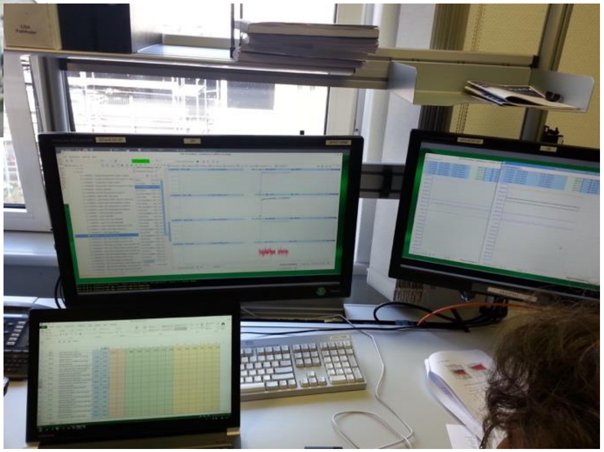




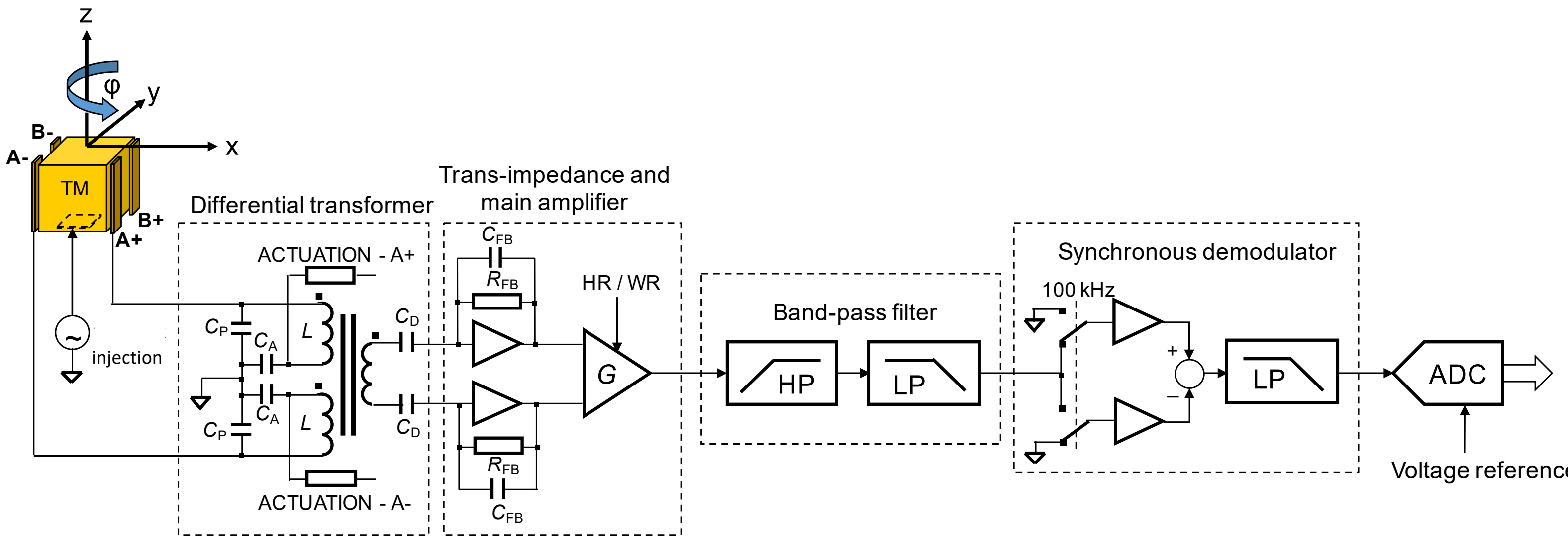
LPF Commissioning and Operations go to PISA







IS FEE Sensing



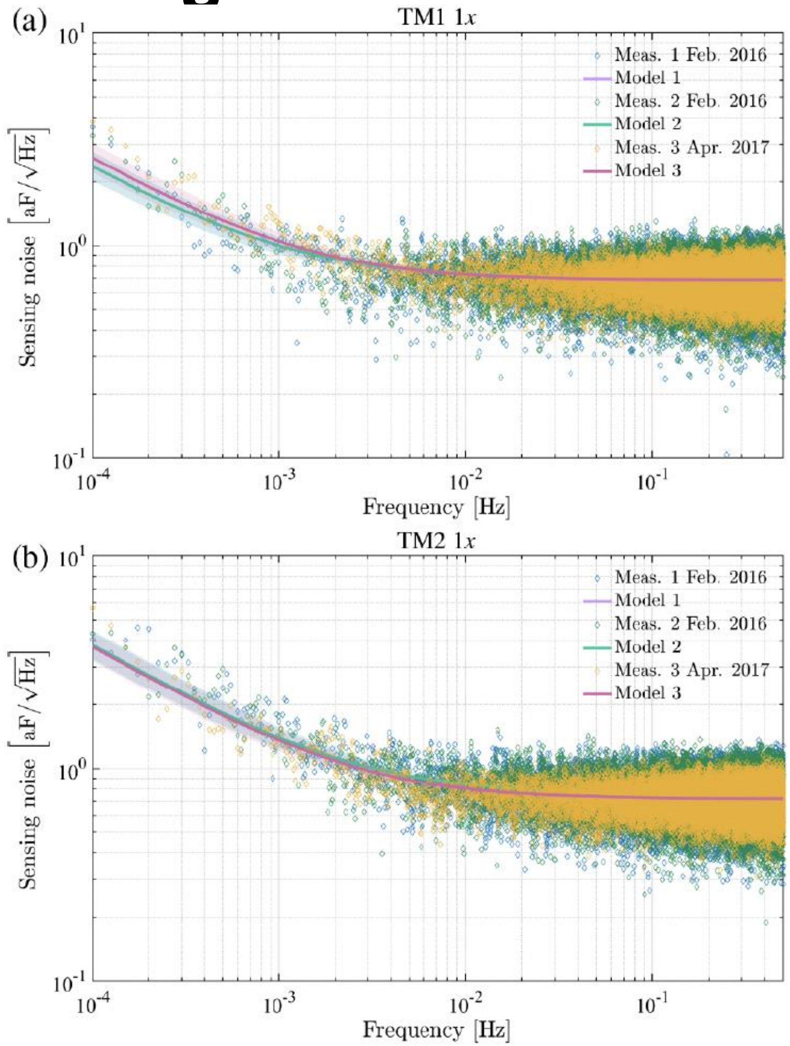
Items of the sensing chain:

- Sensing bridge
- TIA and amp
- Bandpass filter
- Demodulator
- Lowpass filter
- ADC

IS FEE Performances - Sensing

- Sensing performances down to low frequencies measured during Feb 2016 (Commissioning) and Apr 2017 with TM grabbed
- TM grabbed allows to isolate the system from the closed loop dynamics so the performance of the FEE can be assessed
- The data can be interpreted with a phenomenological model

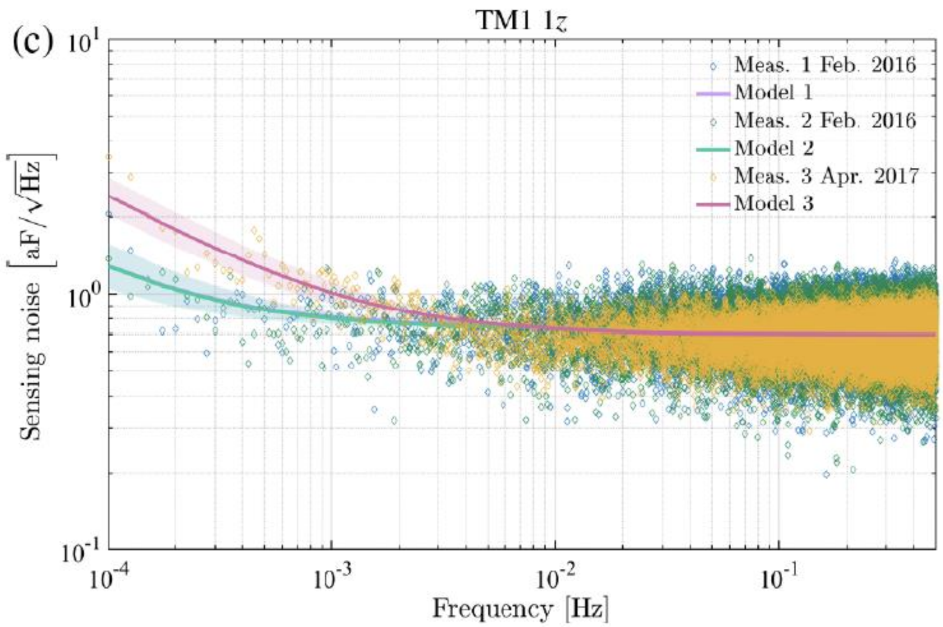
$$\left(1\,\frac{aF}{\sqrt{Hz}}\right)^2\left[1+\left(\frac{1\,mHz}{f}\right)\right]+\left(\Delta C\,30\times10^{-6}\,\frac{aF}{\sqrt{Hz}}\right)^2\left(\frac{1\,mHz}{f}\right)$$



PHYSICAL REVIEW D 96, 062004 (2017)

IS FEE Performances - Sensing

- White noise dominated by the thermal noise of the sensing bridge
- Low frequency coupled with the TM displacement. Mainly contributed by the injection voltage noise
- Extra low frequency probably contributed by the thermal dependence of the sensing gain and the low frequency tail of the ADC voltage reference noise

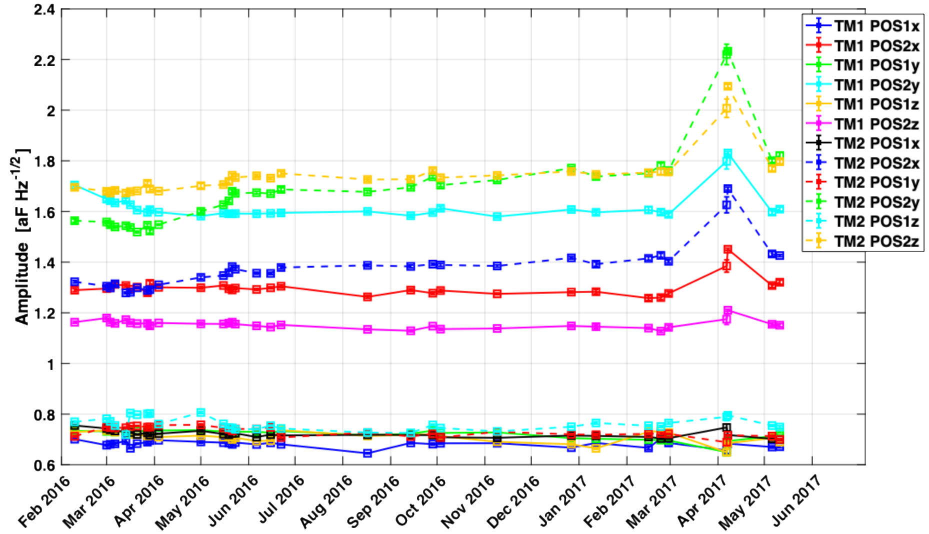


$$\left(1\ \frac{aF}{\sqrt{Hz}}\right)^2\left[1+\left(\frac{1\ mHz}{f}\right)\right]+\left(\Delta C\ 30\times10^{-6}\ \frac{aF}{\sqrt{Hz}}\right)^2\left(\frac{1\ mHz}{f}\right)$$

PHYSICAL REVIEW D 96, 062004 (2017)

IS FEE Performances - Sensing

- Monitored sensing noise between [0.3 – 0.49] Hz
- Measurements spans from Feb 2016 to Jun 2017
- Channels 1# were performing at the limit of the sensing bridge thermal noise
- Channels 2# show excess noise and extra sensitivity to drifts and external perturbations (April 2017 anomaly)

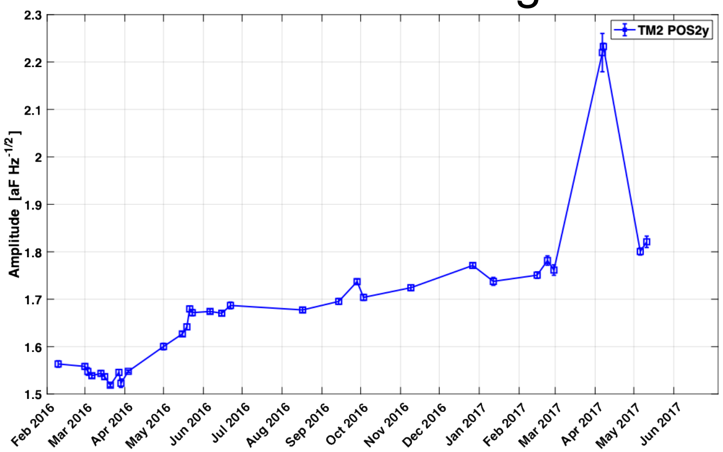


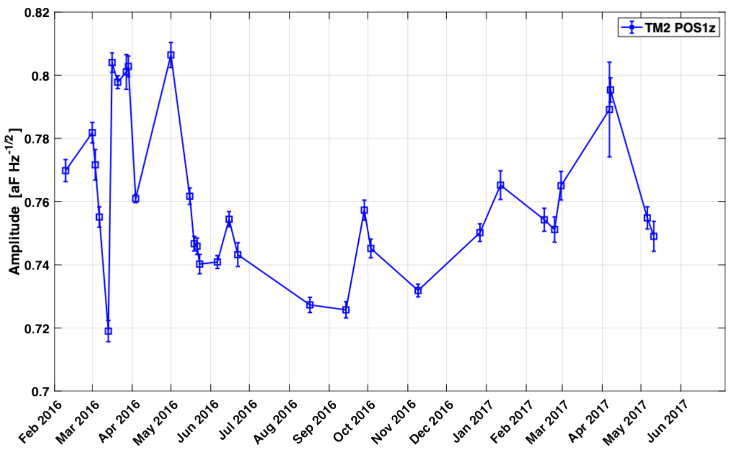
PHYSICAL REVIEW D 96, 062004 (2017)

IS FEE Performances – Sensing – Drifts

- Excluding April 2017 from the analysis
- A drift is observed which is stronger at the beginning of operations
- The origin is not yet clearly identified
- Not all the channels show the same 1# do not show clear difts

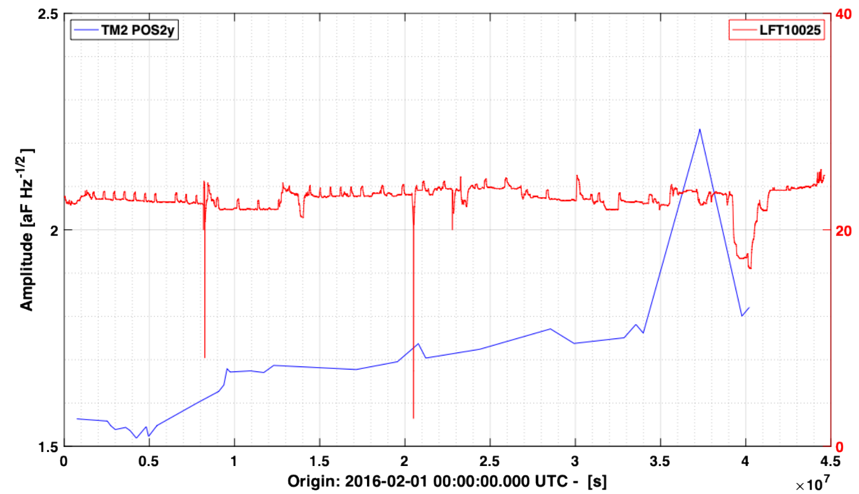
Drifting channel



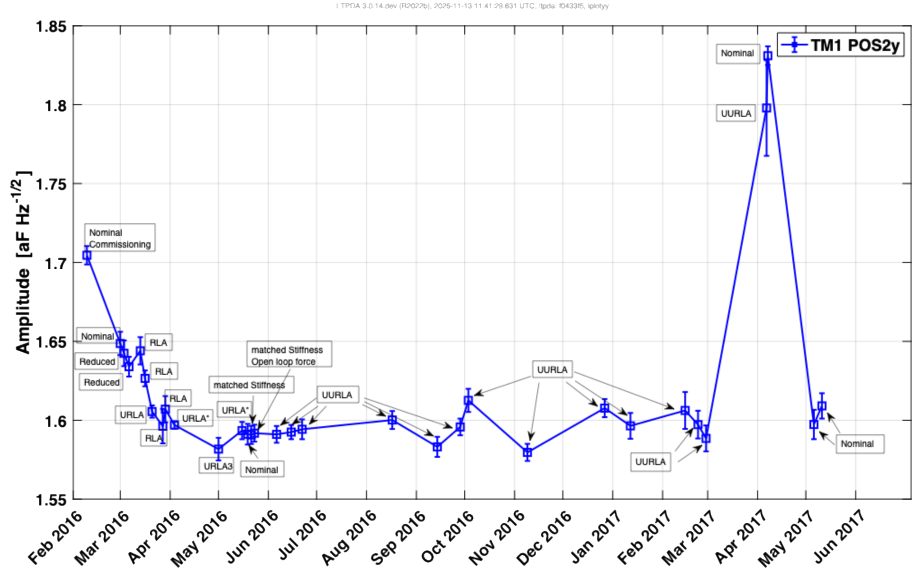


Non drifting channel

IS FEE Performances – Sensing – April 2017 Anomaly

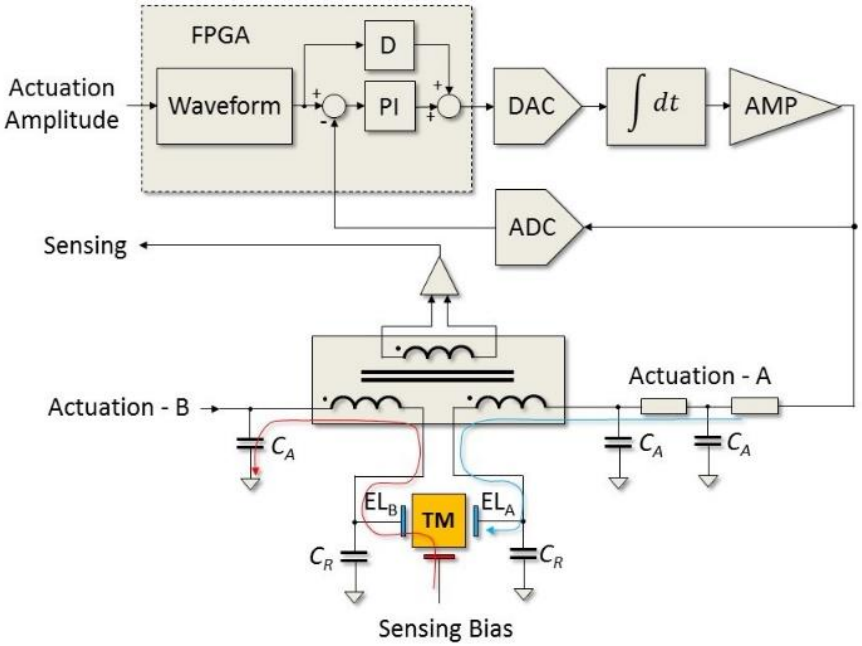


- Does not correlate with temperature (change in the gain and any thermal related noise)
- Does not correlate with TM displacement (change in the coupling with the injection voltage noise)
- Does not clearly correlate with the injection voltage amplitude values (change in the gain)
- Does not correlate with the actuation authority (voltage commands amplitude, cross-talk)
- Does not depend upon DRS operations. On April 24, 2017 DRS ST7 was operating. A segment of noise in HR is selected. The ASD shows results compatible with the expectations i.e. for both TM2 POS2y and TM2 POS2z we have ~ 1.79 aF/sqrt(Hz)



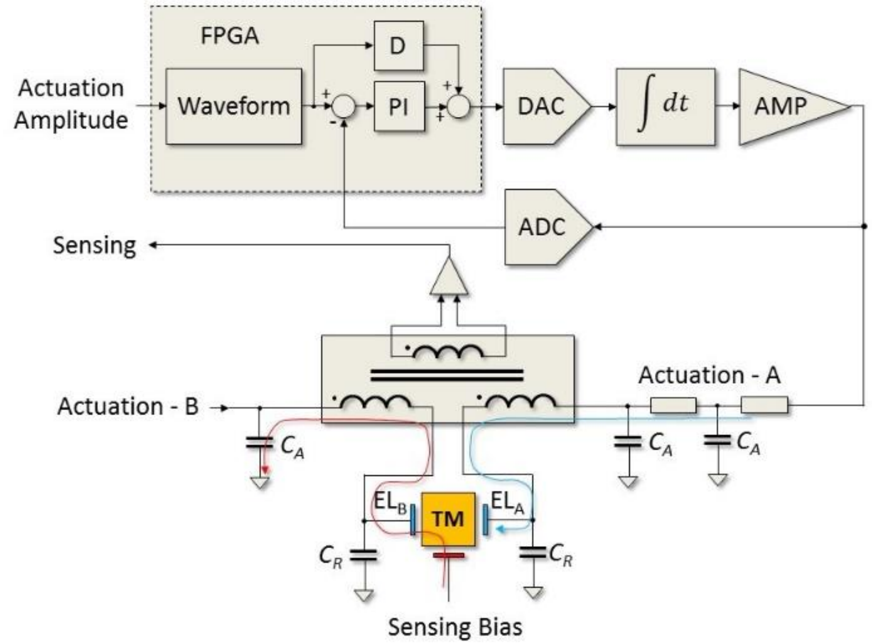
IS FEE Actuation Scheme

- Commands are received from the DFACS
- Digital waveforms are created in the FPGA and mixed / rounded
- The waveform is applied to the electrode by a feedback-controlled DAC
- The items in the feedback path are critical for performances
- Noise below ~ kHz on the forward path to the electrode is effectively suppressed by the loop



IS FEE Actuation Key Performance Drivers

- Actuation amplitude stability
  - Affected mainly by gain instabilities in the feedback path e.g. voltage reference of the ADC, temperature dependence of the gain
- Actuation voltage noise. In-band DC noise
  - E.g. offset instability
- Actuation additive noise
  - In-band down conversion of additive noise at the frequency of the actuation voltages
- References:
  - PHYSICAL REVIEW D 109, 102009 (2024)
  - PRL 118, 171101 (2017)



$$F_q(t) = \frac{1}{2}\left|\frac{\partial C_q^*}{\partial q}\right|\left(V_{m_1}^2(t) + V_{m_2}^2(t) - V_{m_3}^2(t) - V_{m_4}^2(t)\right)$$

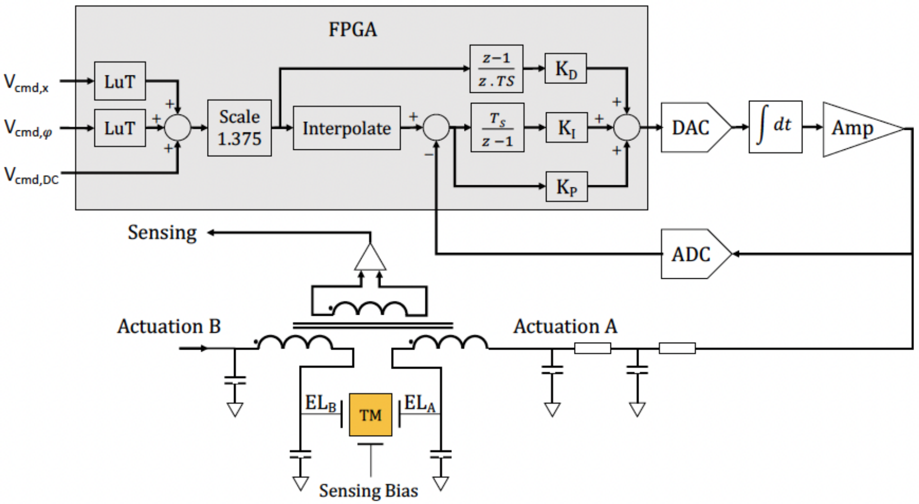
Fluctuations of the voltage amplitude determines force/torque noise

$$S_{ACTg_x} = R_x^2\left(\gamma_{\phi C}^2 + \gamma_{\phi 0}^2\right) S_{\alpha UC} + \frac{2}{M}\left|\frac{\partial C_x^*}{\partial x}\right| R_x \gamma_{\phi 0} S_{ADD}$$

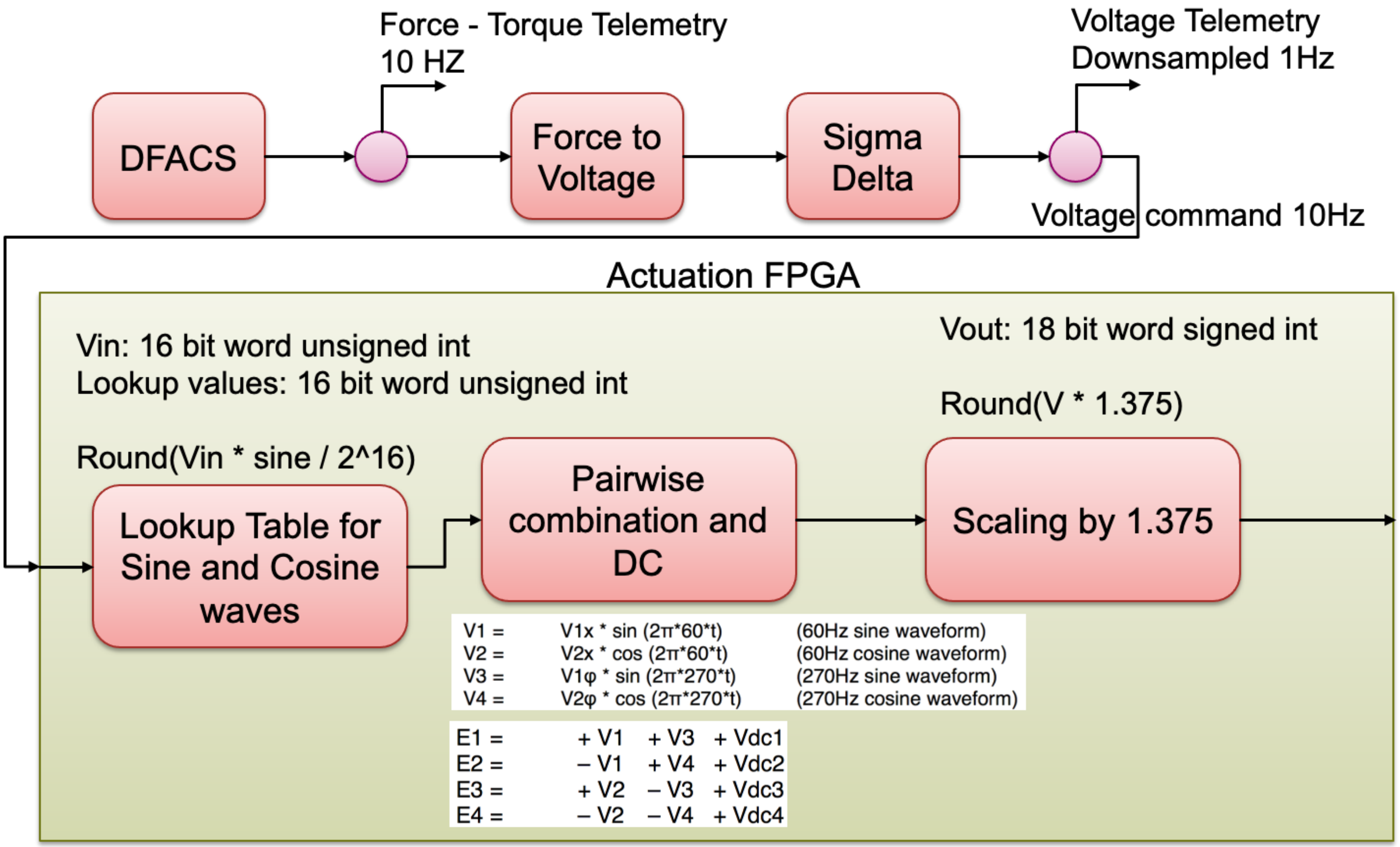
Non actuated channels are affected too!

IS FEE Actuation Waveform Accuracy

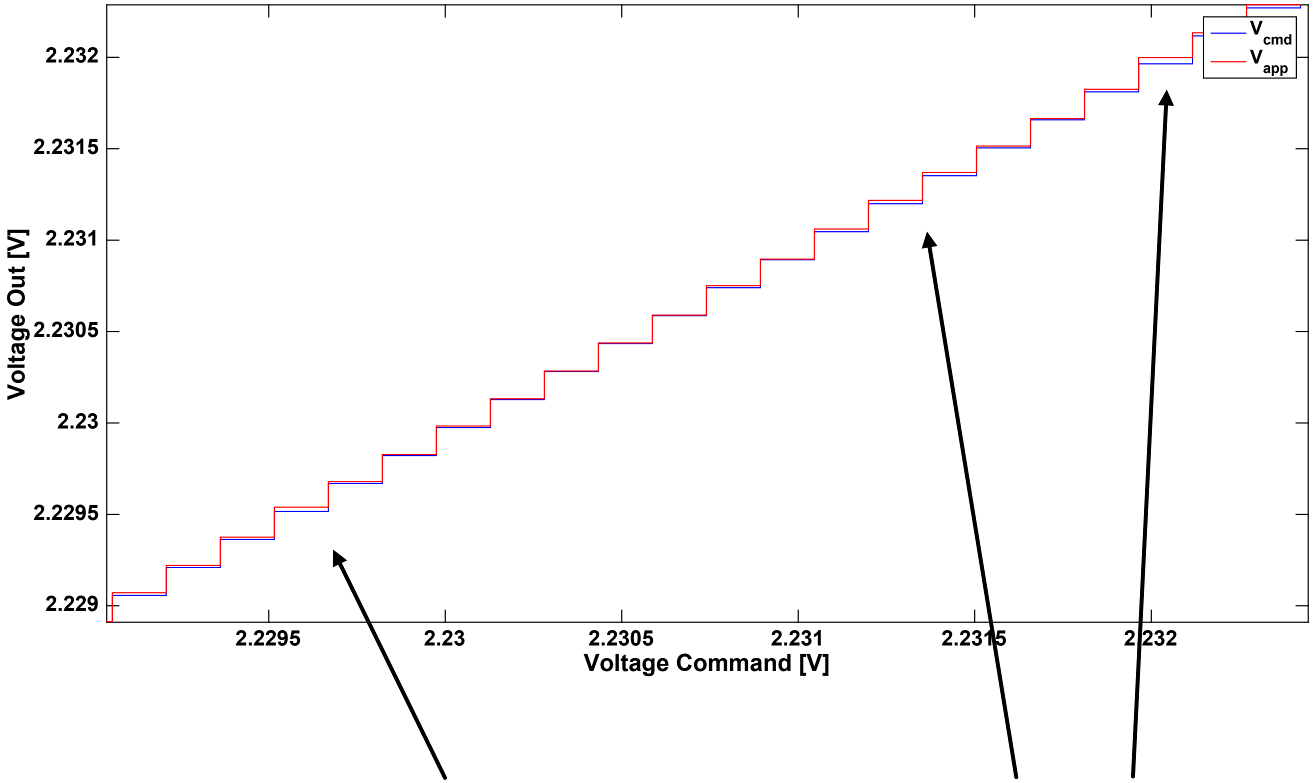
- The science observable: $\Delta g = \ddot{x} - g_{cmd} - g_{non-inertial}$
- Commanded forces are applied via voltages provided by the FEE
- "Ideal" commanded forces/torques were available from telemetry
- Anomalies in the low frequency behavior of Δg were observed
- The "ideal" commanded forces/torques were too ideal to be representative



IS FEE Actuation Waveform Accuracy

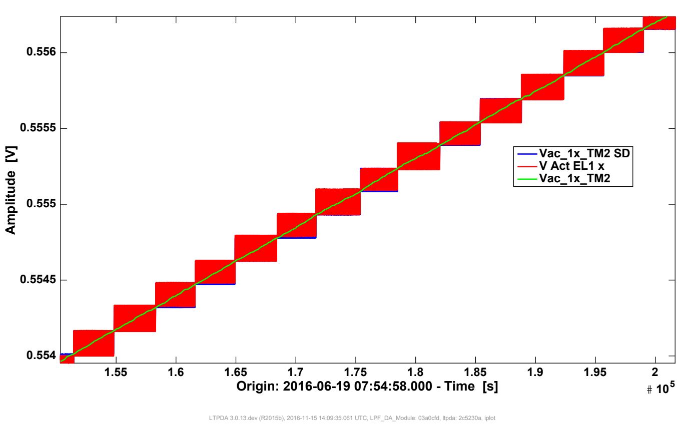


IS FEE Actuation Waveform Accuracy

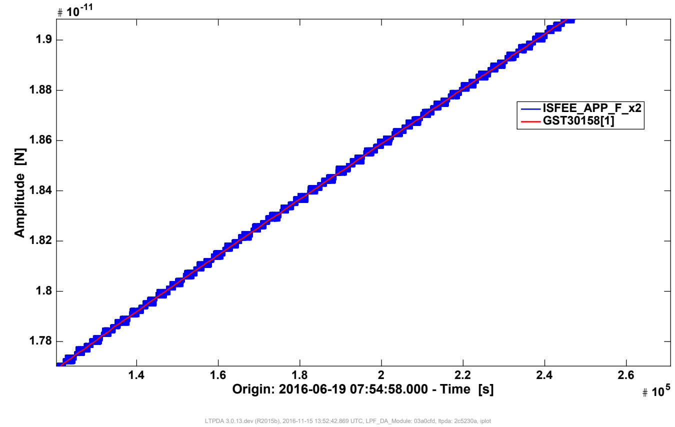


Differences between the commanded and applied voltages
Fully deterministic i.e. Predictable and repeatable

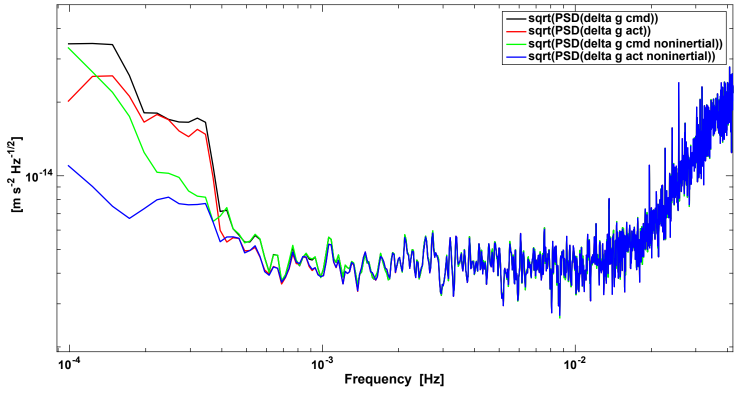
IS FEE Actuation Waveform Accuracy



Green: Is the "ideal" commands
Blue: Is the actual command received by the FEE
Red: Is the applied voltage at the electrodes



Blue: Is the Ideal force command
Red: Is the applied force



Delta g correction LPF June 19th noise run

Green: Is with "ideal" commanded forces
Blue: Is with actuated forces (derived from actuated voltages)

The Path to LISA GRS FEE

Departures from LPF Heritage are driven by:

- The need for more efficient AIT or better reliability
- Changes of requirements
- LPF Lesson Learned (LISA-ETH-INST-LL-001 GRS FEE Lesson Learned from LPF)

Approach to validate unit performances.

An elegant BB model is manufactured and currently being tested.

AIT Optimization and Reliability

- LPF GRS FEE partitioning scheme is changed in order to have one GRS FEE unit per GRSH

Requirements Changes

- Higher actuation AC voltage in WR mode
- Higher actuation AC voltage in HR mode
- New system clock frequency and synchronization scheme
- New system DFACS cycle frequency
- Longer GRS FEE to GRSH harness

Lesson Learned

- Need for better actuation accuracy
- Actuation to sensing cross-talk
- Actuation lock anomaly

End of the presentation