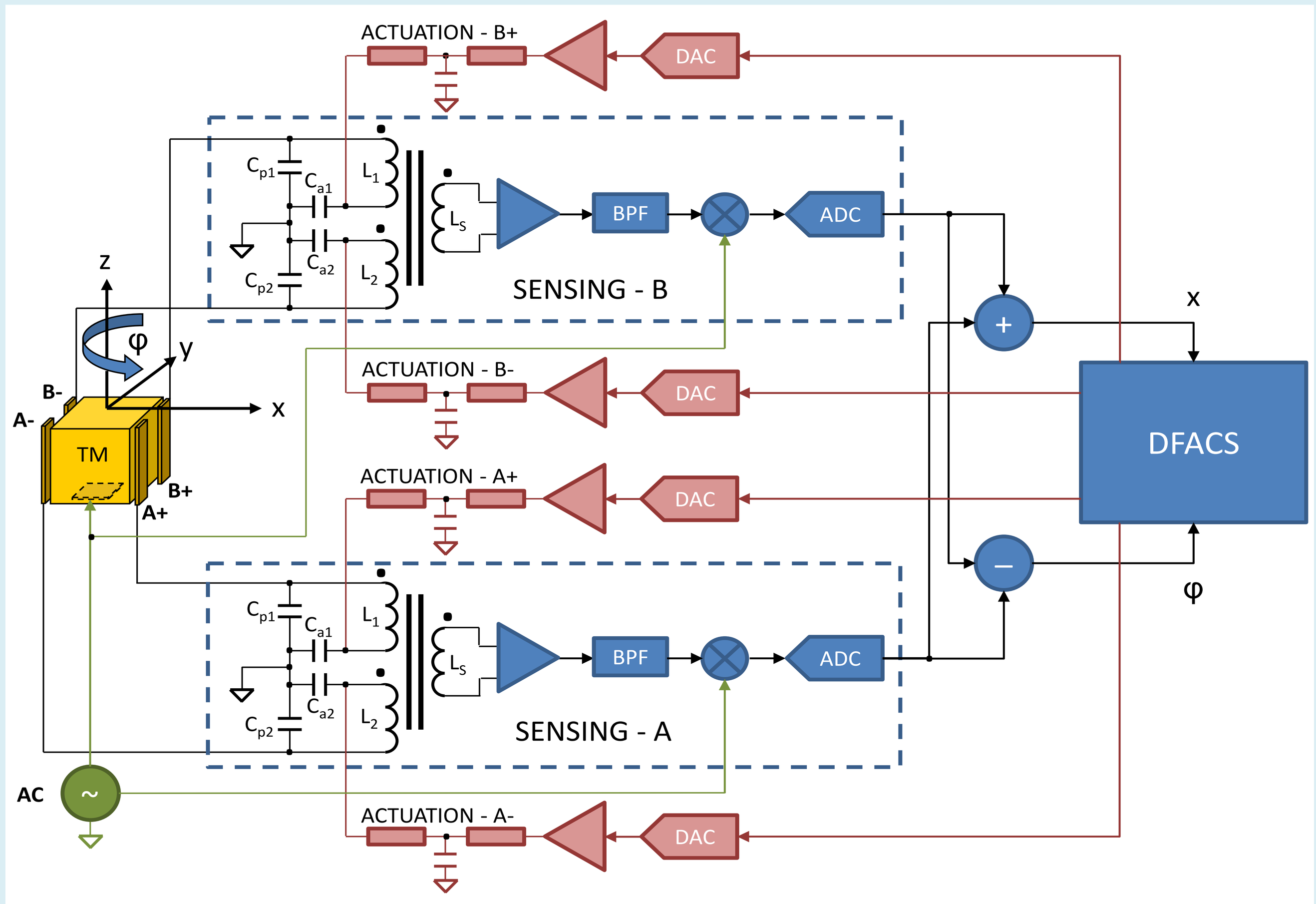
GRS Electronics for a Space Borne Gravitational Wave Observatory

Davor Mance, Peter Zweifel, Luigi Ferraioli, Jan ten Pierick and Domenico Giardini
Department of Earth Sciences, Institute of Geophysics, ETH Zürich

Gravitational Reference Sensor (GRS) Front End Electronics

The Test Mass (TM) is electrostatically suspended between surrounding electrodes and its motion, e.g. along x or φ causes an imbalance in capacitance, i.e. in currents of primary windings in both transformer bridges (between electrodes A+/- and B+/-). The preamplifier detects the differential current in the transformer secondary and converts it to a voltage, which is then band-pass filtered (BPF), converted into DC voltage by a demodulator and then finally digitized by an Analog to Digital Converter (ADC).

The TM is biased by 100 kHz AC signal via separate injection electrodes. To allow for a high sensitivity of capacitive measurement, the transformer with a high quality factor Q is operated at a resonance, matching the injection bias frequency, for which capacitors (Cp) are added in parallel with primary windings.



In order to reduce the stray acceleration on TM or to add some guidance, the force signals are provided by numerically synthesized AC waveforms at low audio frequencies (60 – 270 Hz). To apply strong forces on TM during TM release or spacecraft maneuvers, large AC voltages are needed (120 V). The force signal for each electrode is Digital to Analog Converted (DAC) and amplified by a corresponding Drive Voltage Amplifier.

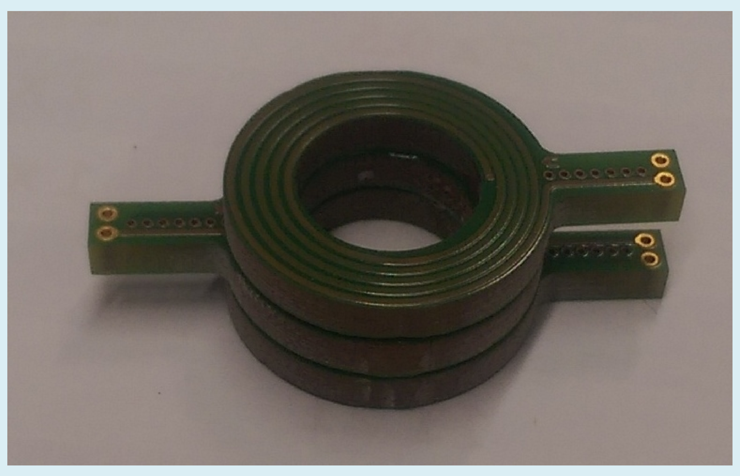
As shown on figure, two capacitive measurements are combined to calculate TM translation (x) and rotation (φ). Similarly, other 8 electrodes (not shown for clarity) are used to derive remaining TM movements in y – θ and z – φ axes. TM attitude and control forces are calculated by the Drag-Free Attitude Control System (DFACS) software located in the On-Board Computer (OBC).

LISA Pathfinder GRS Sensing Performance

The capacitive sensitivity performance is limited by the quality factor (Q) of the differential transformer, whose losses produce thermal noise. To achieve the required noise density floor of 1 aF/√Hz (equivalent to 1.8 nm/√Hz) transformer must have Q > 150. This requires low inter- and intra-winding stray capacitances. In addition, the inductance imbalance between primary windings of < 50 ppm is needed to achieve sensing offset better than 1 µm.

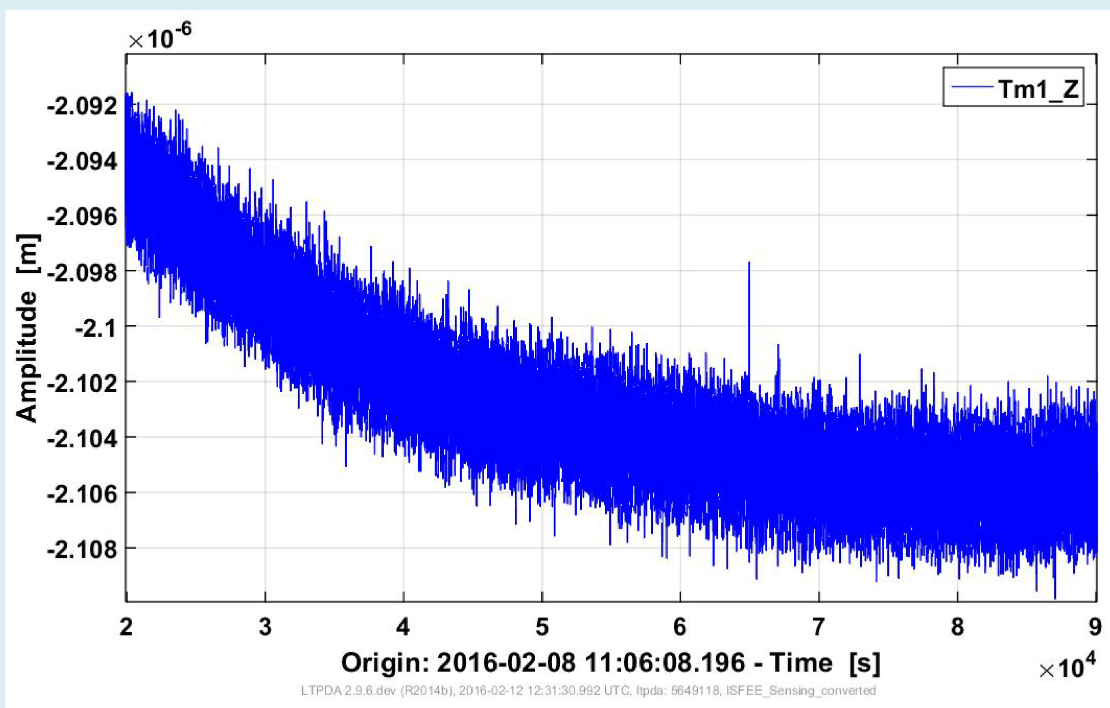
For stability reasons a planar winding design with balance tuning capability was selected. Each winding is made of 16-layer Printed Circuit Board (PCB) and glued after tuning. The transformer is designed by Swiss industry (HES-SO, Sion). A similar transformer winding design, made by ETH, is shown on the right (a stack of three transformer windings).

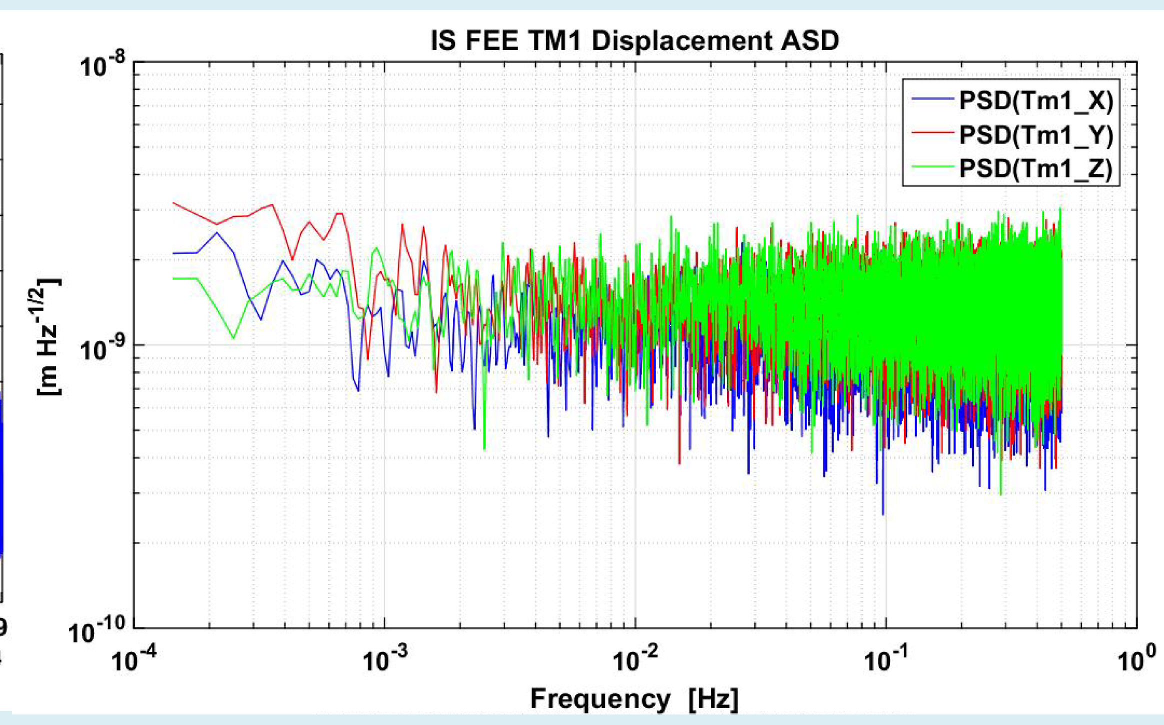
Any sensing bias (AC injection signal) instability mimics TM motion and causes low frequency noise proportional to the TM out-off-center displacement. The amplitude stability of the bias must therefore, be better than 50 ppm/√Hz not to compromise sensing noise performance at maximum TM displacement of ±10 µm (High Resolution performance range). In LISA Pathfinder the 50 ppm/√Hz stability requirement is fulfilled down to 1 mHz.



Test of sensing performance requires a Test Mass simulator, which is a differential capacitance simulator of 6 fF (10 µm TM translation equivalent). Fluctuation of stray capacitances in the simulator can produce low frequency noise and thus mask the true GRS sensing performance.

The sensing performance check is performed in flight with TM grabbed by mechanical fingers in z-axis, which provides better differential capacitance stability than the simulators (6 nm peak-peak). Noise performance at 2 µm TM off-center position in z-axis was found to be 1.4 nm/√Hz and flat below 1 mHz.





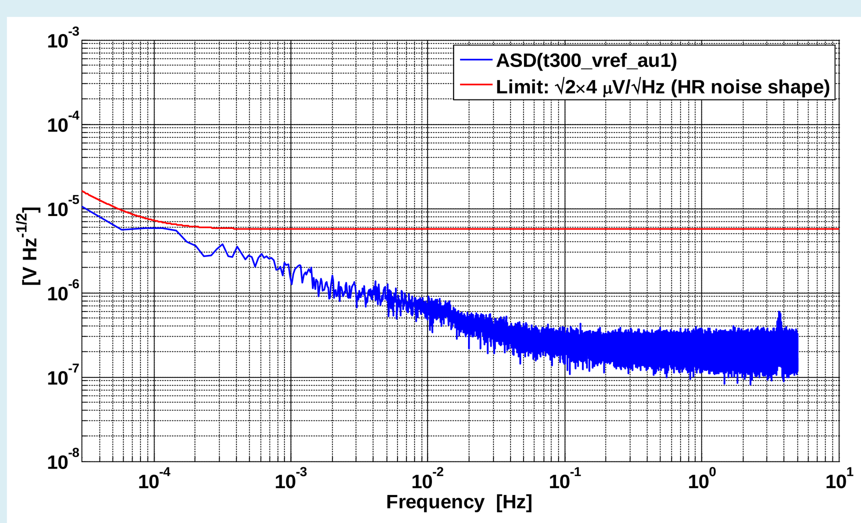
Design Upgrades for LISA

LISA performance in sensing and actuation must extend down to 0.1 mHz for which some design changes are needed. For non-zero TM displacements the injection bias amplitude stability must improve since the amplitude noise density is currently 150 ppm/√Hz at 0.1 mHz (50 ppm/√Hz is Pathfinder requirement at 1 mHz). Furthermore, the 2 ppm/√Hz actuation amplitude stability has to be achieved at 0.1 mHz and the Pathfinder performance is 4-7 ppm/√Hz at 1 mHz and 12-60 ppm/√Hz at 0.1 mHz.

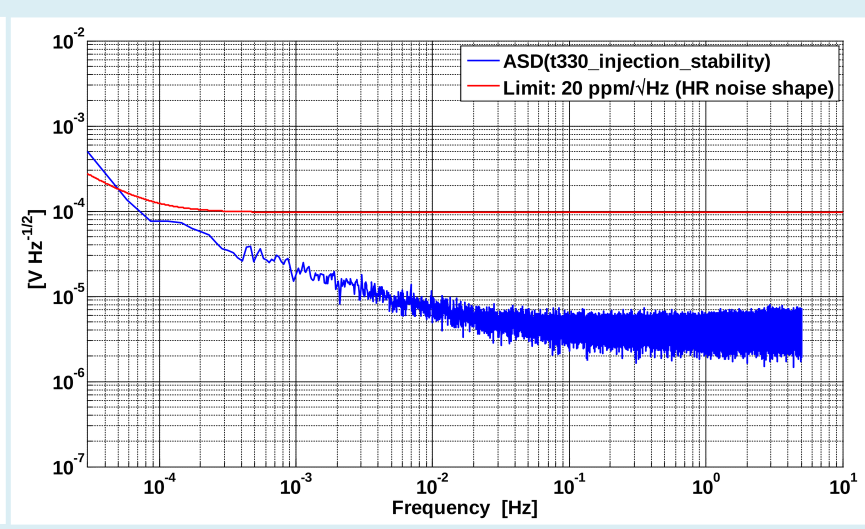
Since the voltage reference circuit is the main driver for the amplitude stability of the sensing injection bias and actuation waveforms, the reference circuit has to be modified. Additional modifications are needed in the actuation control loop where zero-offset (auto-zero) amplifiers shall be used to reduce the low frequency noise.

New prototype of LISA GRS FEE Unit has already been manufactured by ETH Zurich, RUAG Zurich and HES-SO Sion. HES-SO designed the sensing and actuation circuits, RUAG the control electronics, box and integrated the unit. ETH designed the Reference Unit and performed the performance testing on the whole unit. The sensing injection and actuation amplitude stability is already fulfilled for LISA as shown on the right.

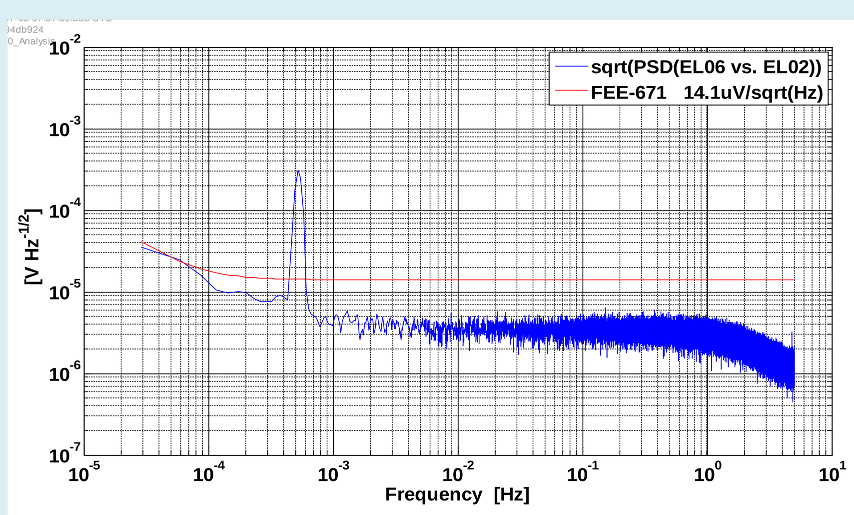
Front End Electronics is on a proven course to LISA.



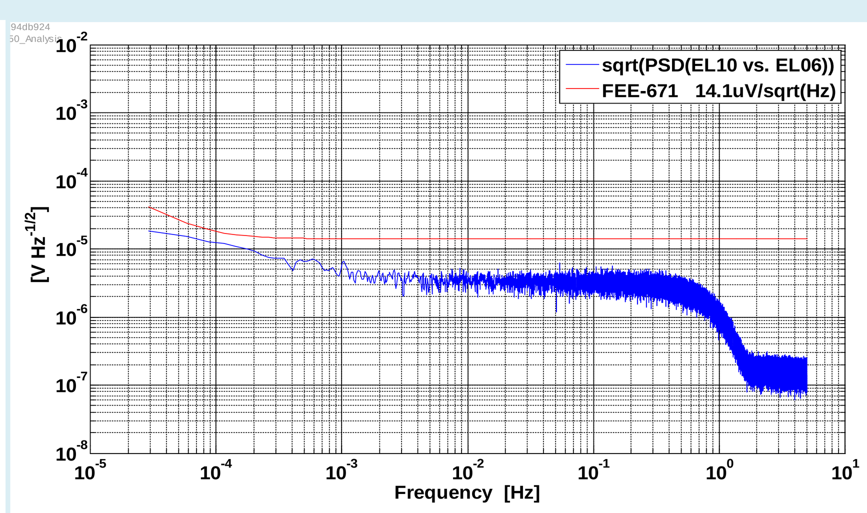
Voltage reference stability (√2 x 1.6 ppm/√Hz limit) for 2.5 V reference



Injection bias stability (20 ppm/√Hz limit) for 4.83 V injection level

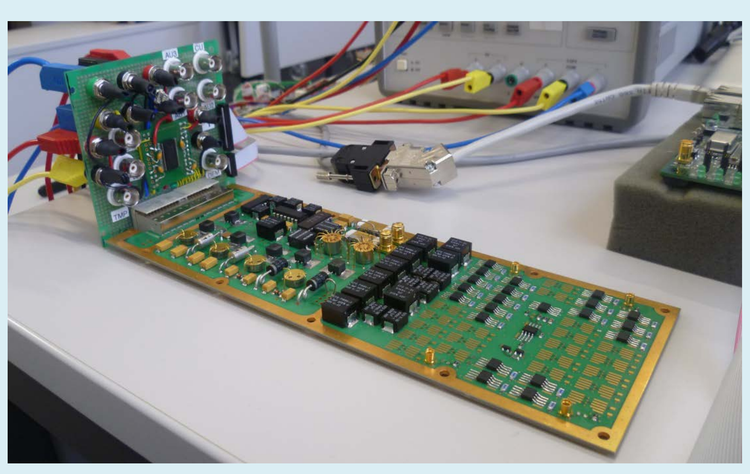


Actuation DC noise (√2 x 10 µm/√Hz limit) for 5 V DC and 5 V AC simultaneous actuation

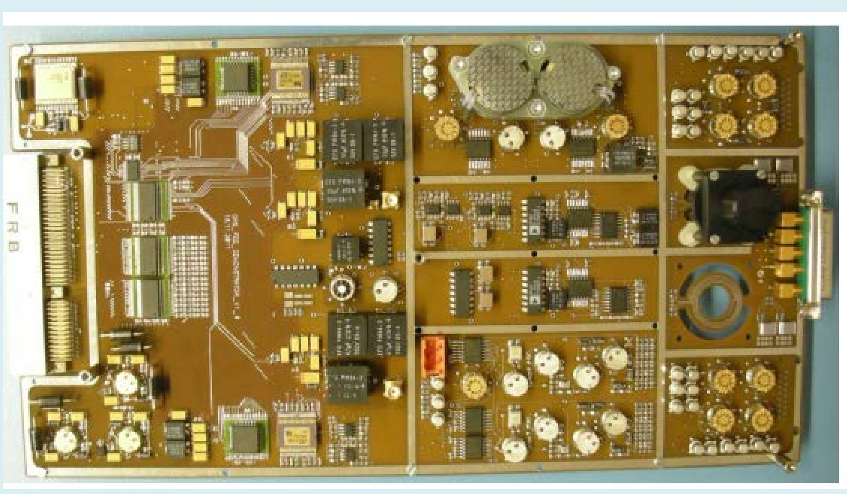


Actuation stability (√2 x 2 ppm/√Hz limit) for 5 V AC actuation

For voltage reference and actuation noise / stability testing a differential measurement was performed for which noise limits are multiplied by factor √2. The voltage reference and actuation DC noise test used uncorrelated voltage reference circuits. The phase of two actuation waveforms could not be tuned to be perfectly equal for which the DC noise plot shows aliasing peak (not well filtered residual sine signal due to phase difference). The allow actuation stability test with well tuned input for locking amplifier, a single reference circuit was used and thus correlated reference noise was removed from measurement, leaving only uncorrelated noise sources.



Reference Unit prototype for LISA



Sensing and Actuation Unit prototype for LISA

Davor Mance et. al., 11th International LISA Symposium, Irchel Campus, University of Zurich, Switzerland, September 05 - September 09, 2016
Email: davor.mance@erdw.ethz.ch