LISA

Beyond Einstein: From the Big Bang to Black Holes

The LISA Acceleration Noise Budget and Its Hardware Implications

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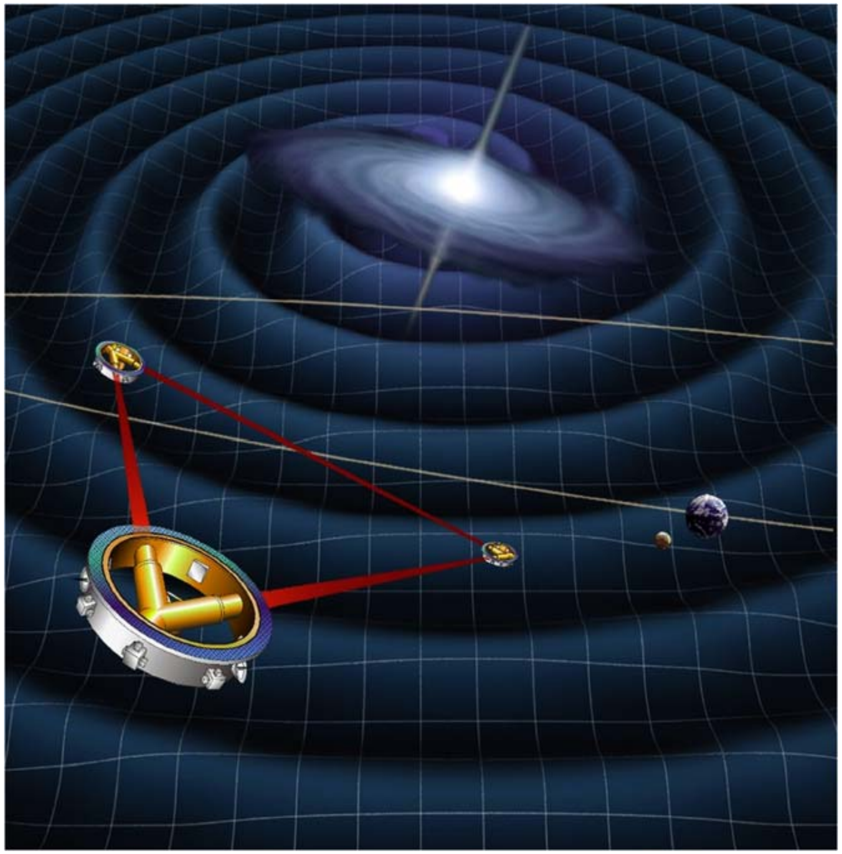
esa

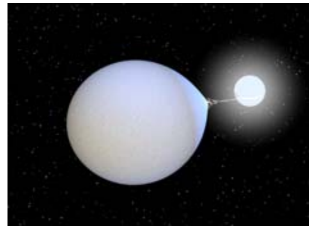
LISA: Laser Interferometer Space Antenna



- LISA is a joint NASA-ESA mission to design, build and operate a space-based gravitational wave detector.
- Launch ~2018.
- The 5 million kilometer long antenna will consist of three spacecraft orbiting the Sun in a triangular formation.
- Space-time strains induced by gravitational waves are detected by measuring changes in the separation of fiducial masses with laser interferometry.

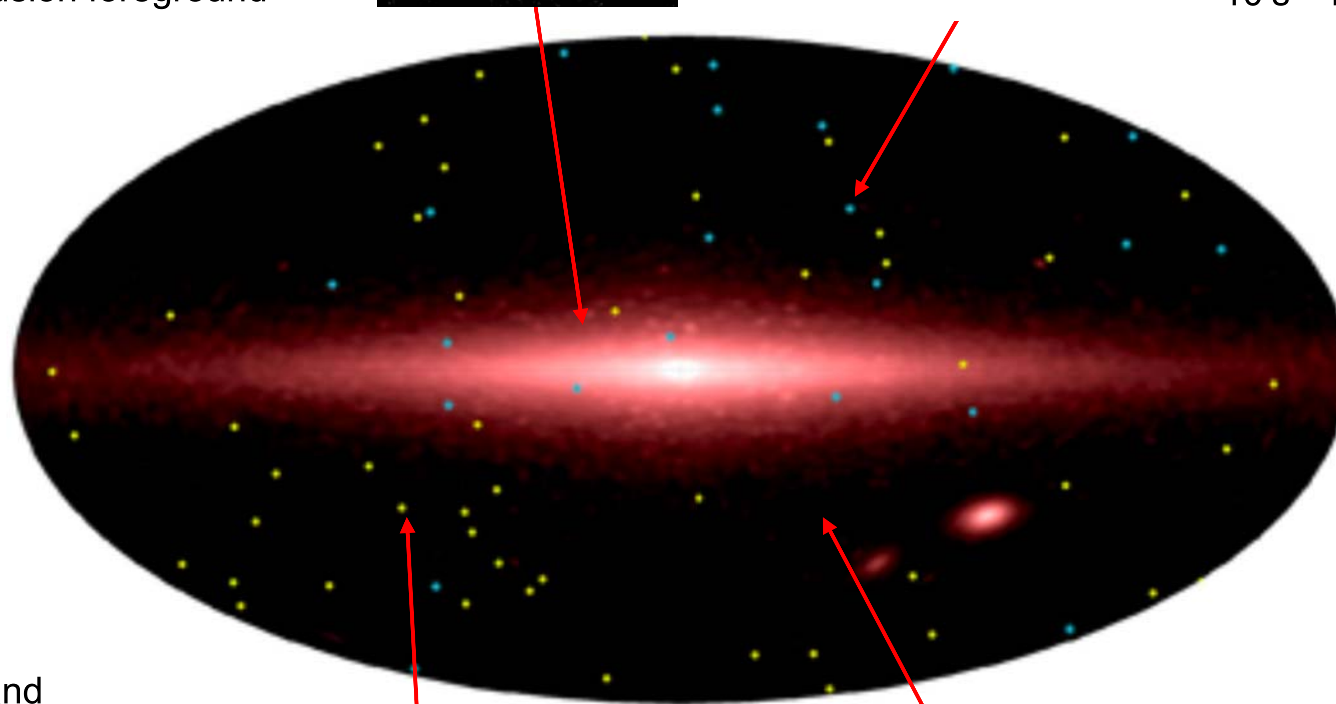
The LISA Sky

Ultra-compact binaries
- *~1 $M_\odot$*
- Galactic and extragalactic
- 1000's - 10,000
- Confusion foreground

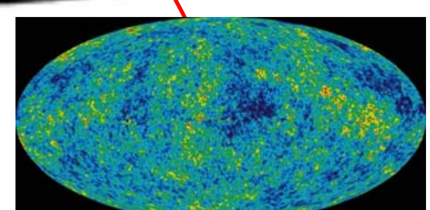


QuickTime™ and a
FF (Uncompressed) decompressc
are needed to see this picture.

Extreme mass-ratio inspirals
- *~10/ 10^6 $M_\odot$*
- *$z < 1$*
- 10's - 100 per year

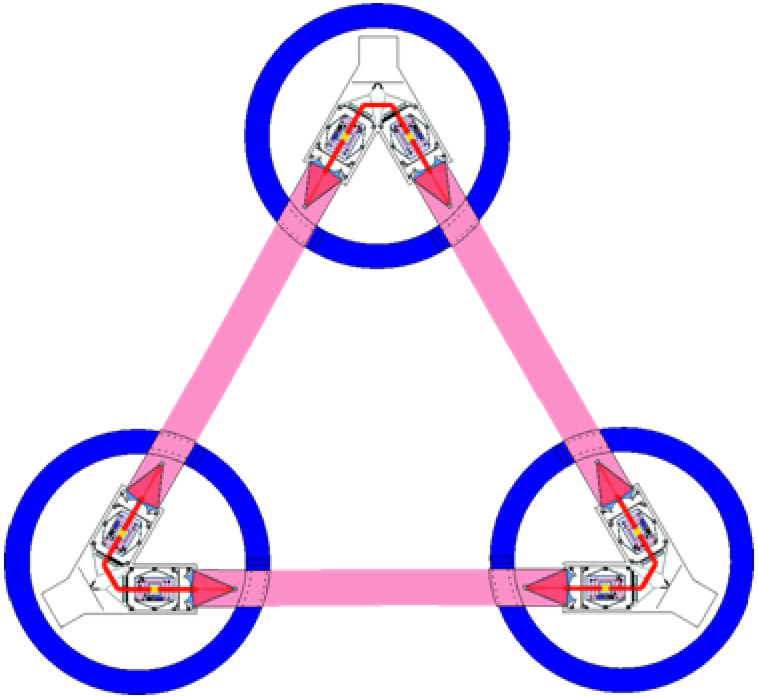


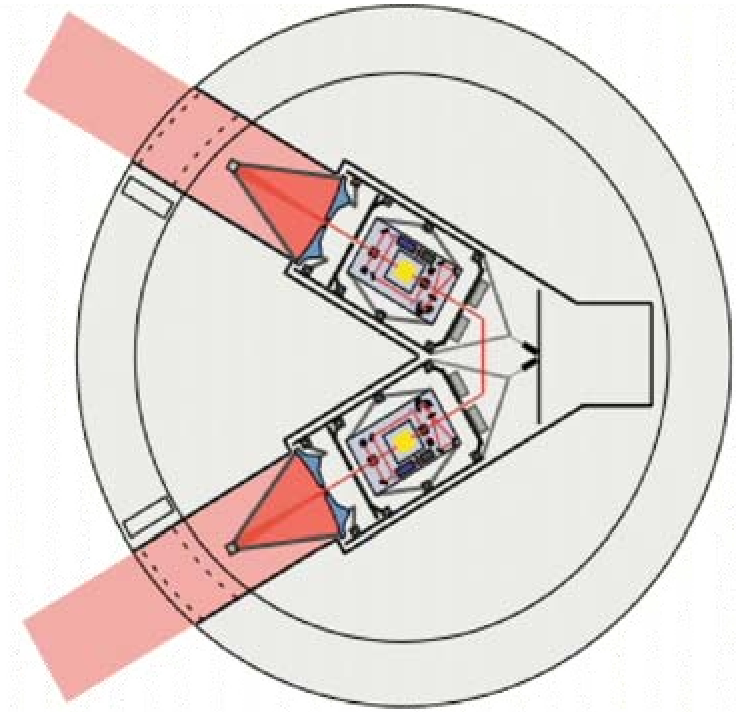
Massive and intermediate-mass black hole binaries
- *10^2 - 10^7 $M_\odot$*
- *$z < 20$*
- 10's to 100 per year



Cosmological back-grounds, bursts and unforeseen sources

LISA Overview

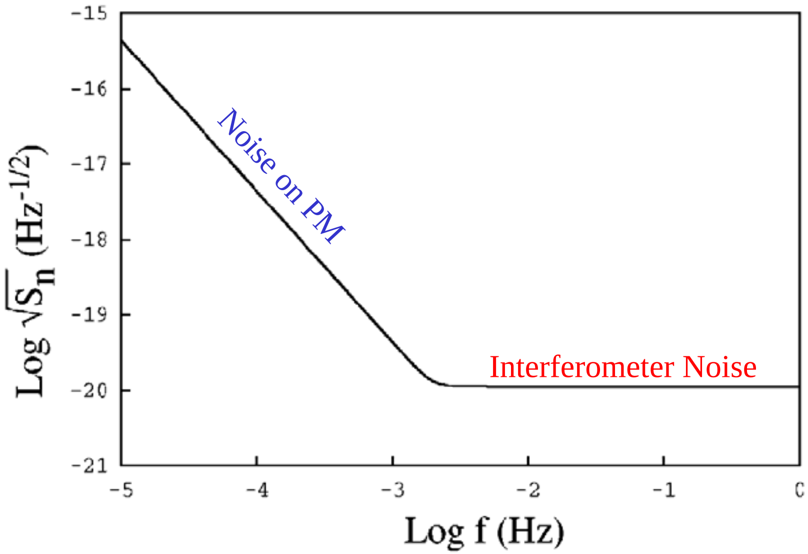


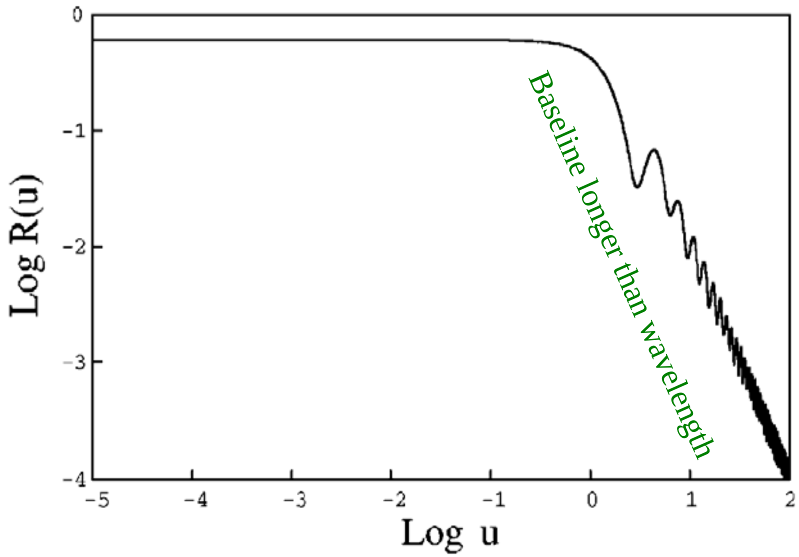


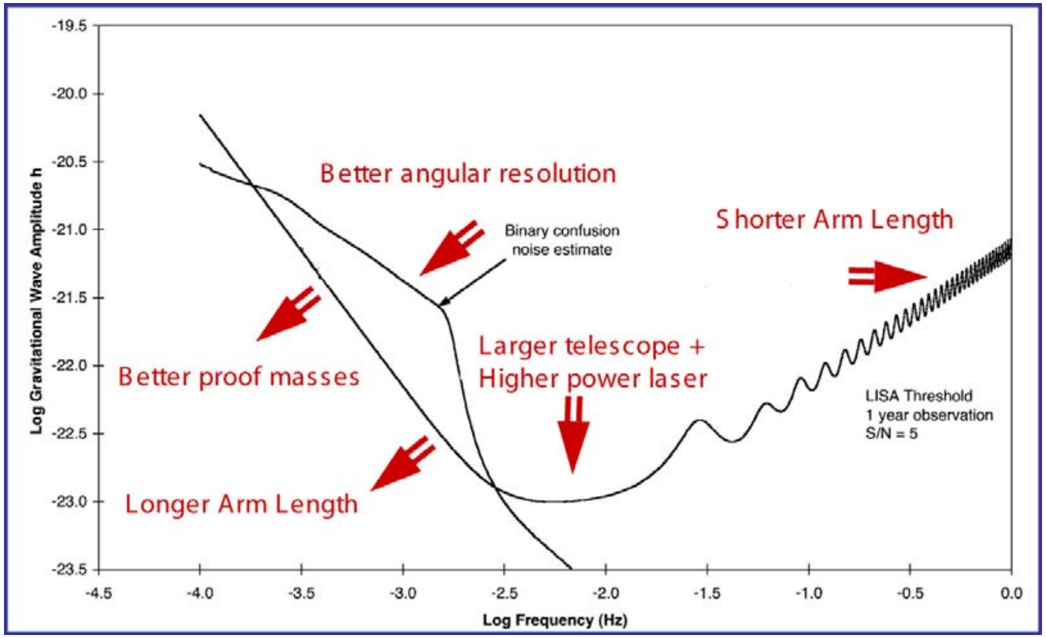
- Three interacting spacecraft make up the “science instrument”
- Measure time-varying strain in space-time by interferometrically monitoring changes in three 5 million kilometer long arms.

- Each spacecraft hosts two optical benches.
- The spacecraft protects its two proof masses from all external disturbances.

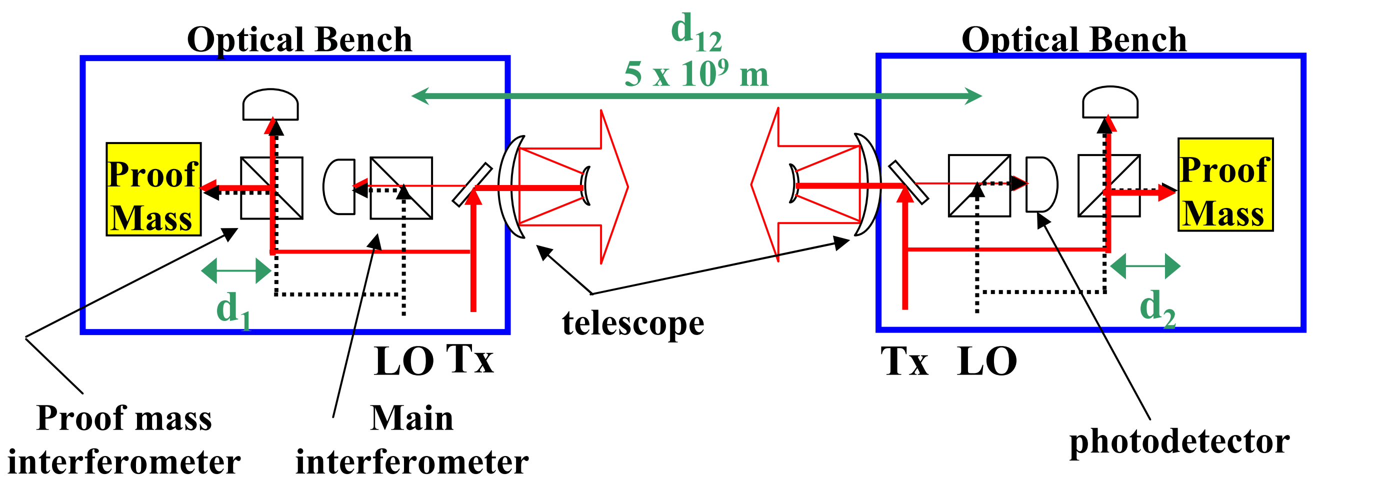
LISA Frequency Response

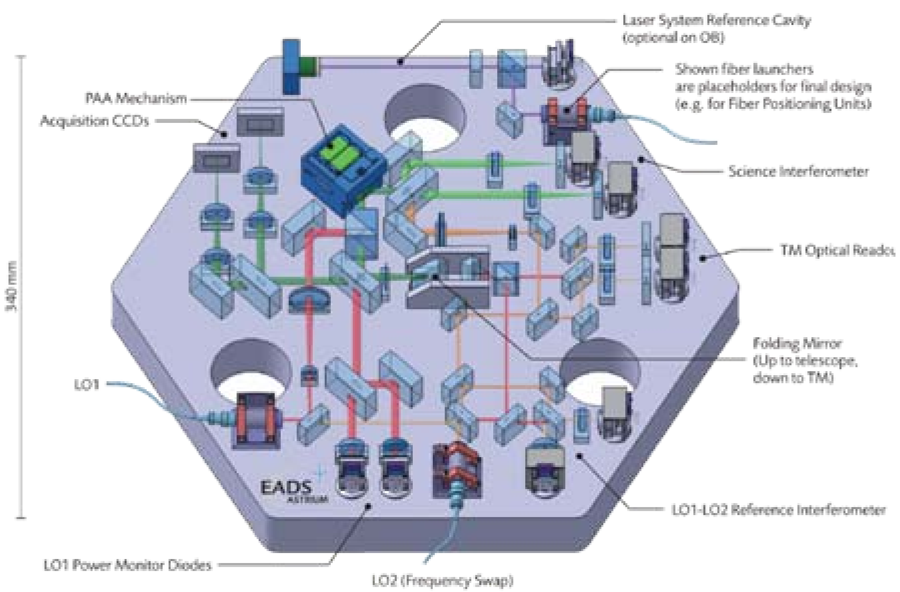


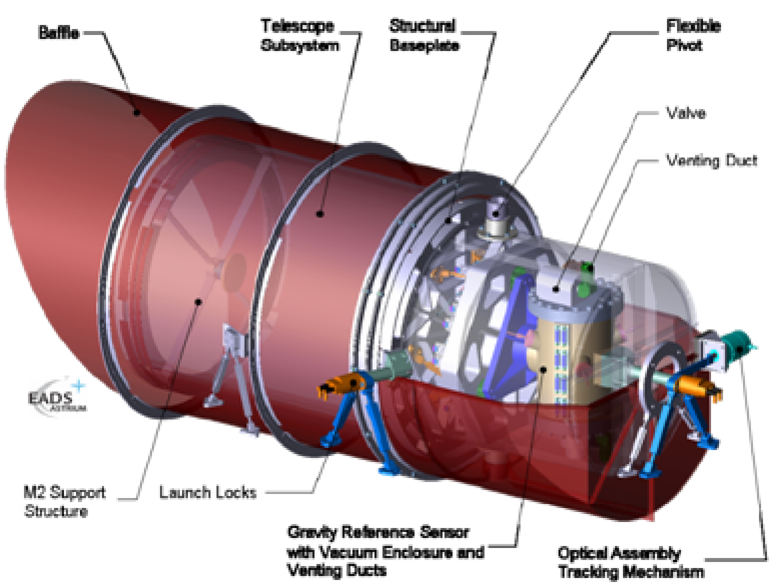




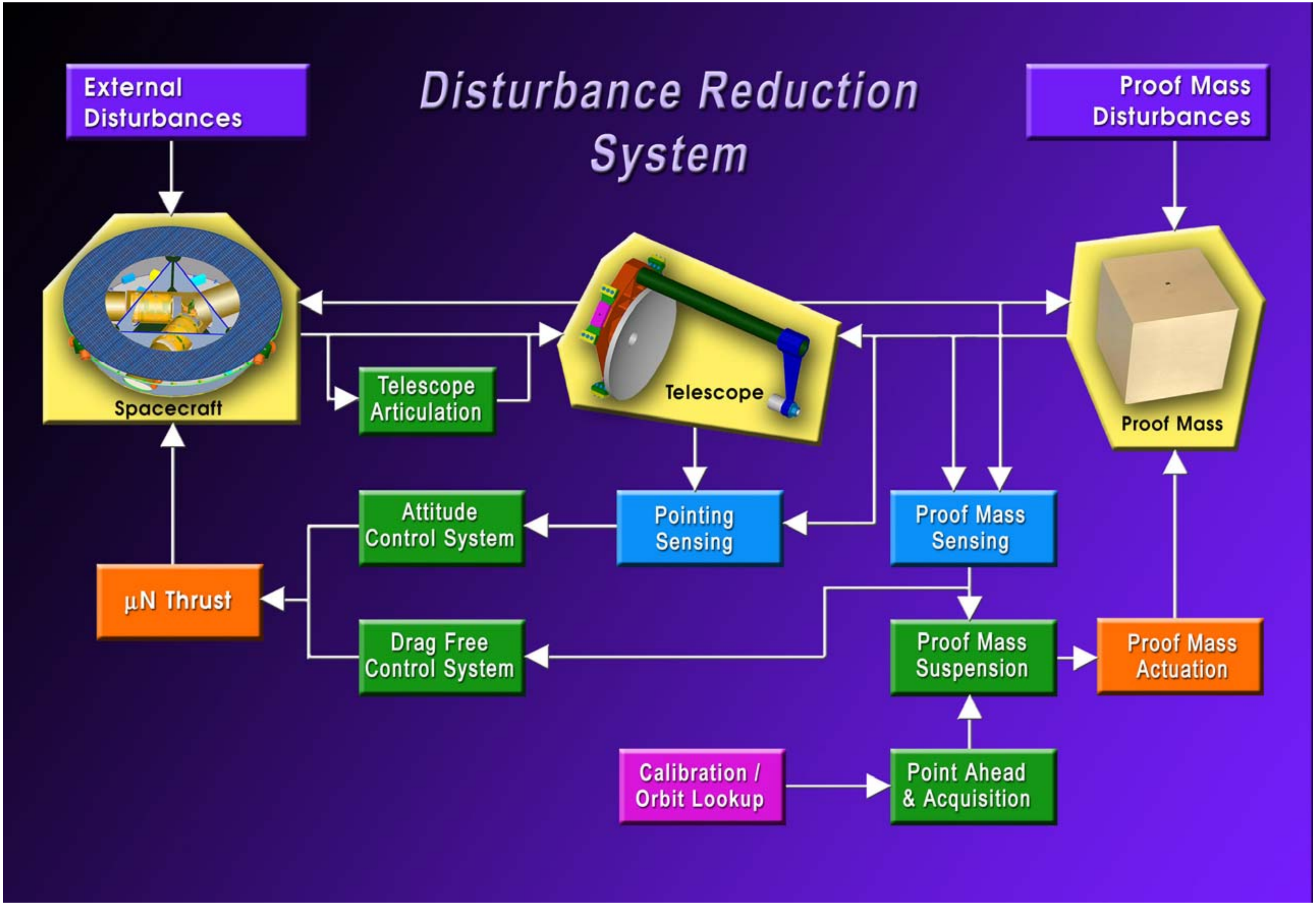
Interferometry Measurement System



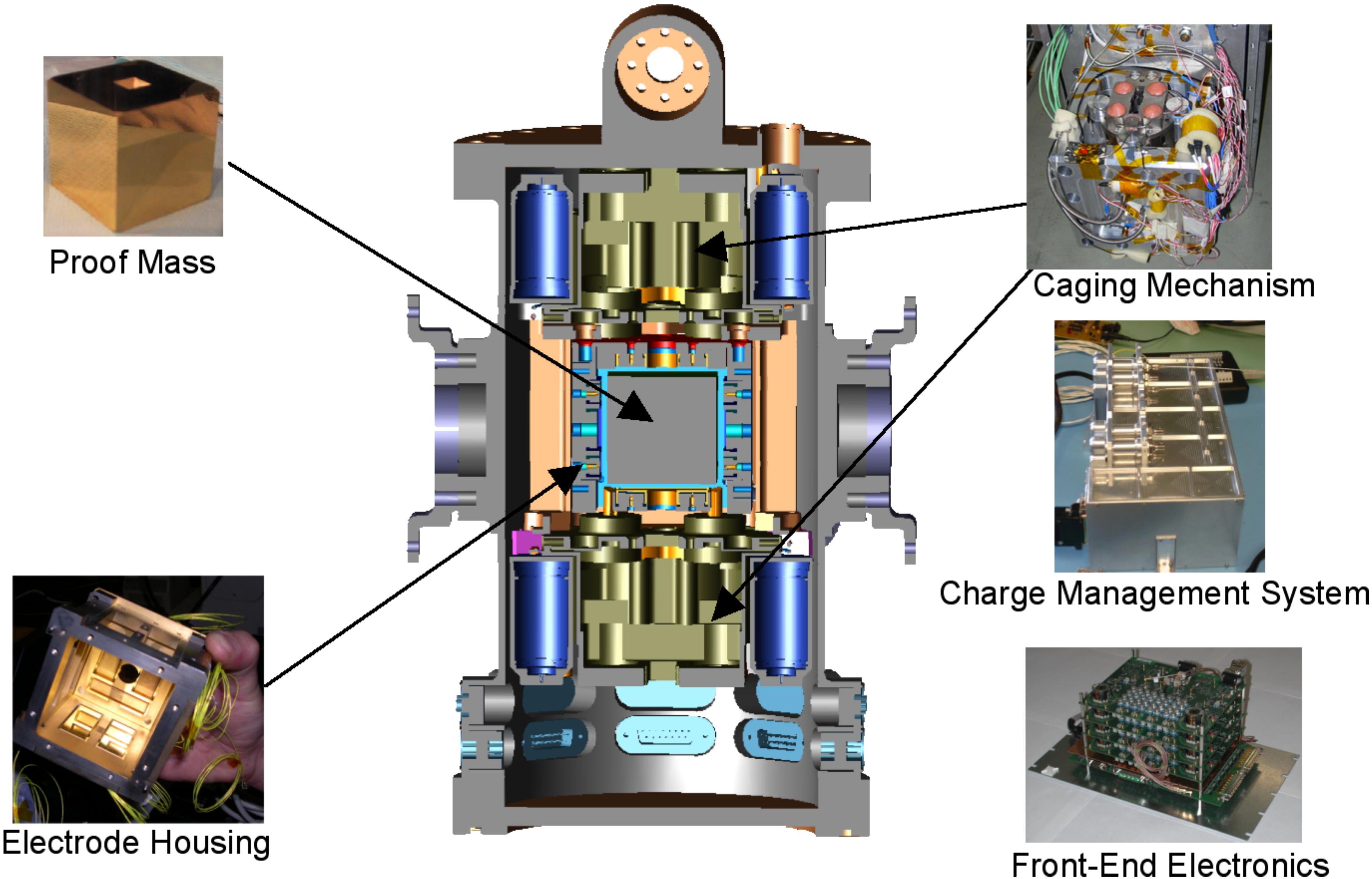




Disturbance Reduction System (DRS)

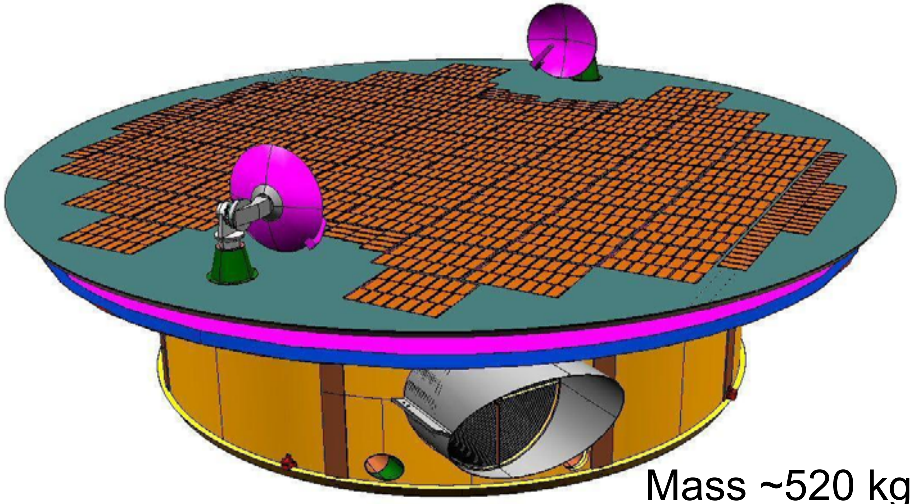


Gravitational Reference Sensor



LISA Spacecraft

Subsystem	Attributes
Propulsion	μN Thrusters
Attitude Control System	2 Star Trackers 3 Sun Sensors 2 Sets of Gyros DRS Control Laws
Communications	2 Ka-Band HGAs 4 X-Band Omni LGAs 2 25W TWTAs
Power	Fixed SA, triple junction GaAs 1.04 KWhr Li-Ion Battery
Structures and Mechanisms	Aluminum Honeycomb Composite Separation Sys, HGA drives



Mass ~520 kg

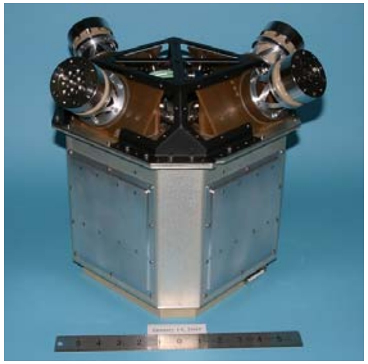
LISA Pathfinder

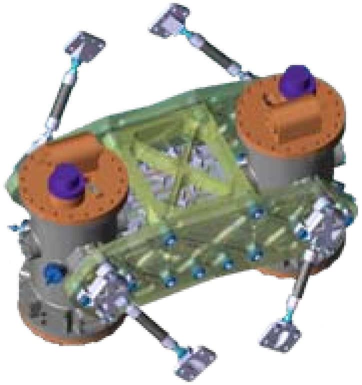
- LISA Pathfinder is an ESA technology demonstration mission for LISA
- European and NASA contributions
- L1 orbit
- Launch date: 2009
- Operational life: 3 months
- The mission will demonstrate in flight:
  - Proof mass in gravitational free-fall with residual acceleration noise less than:

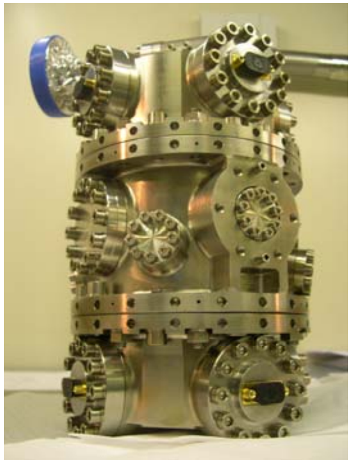
$$\sqrt{S_a(f)} \le 3\times 10^{-14}\left[1+\left(\frac{f}{3mHz}\right)^2\right] \mathrm{m/s^2}/\sqrt{\mathrm{Hz}},$$

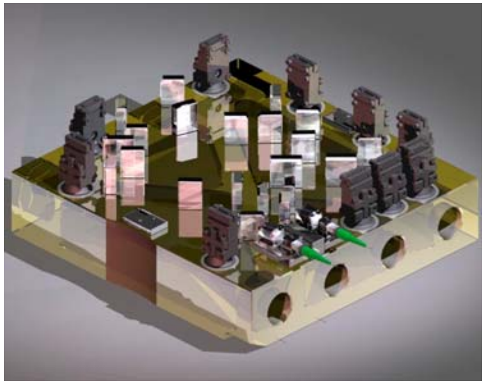
$$1mHz \le f \le 30mHz$$

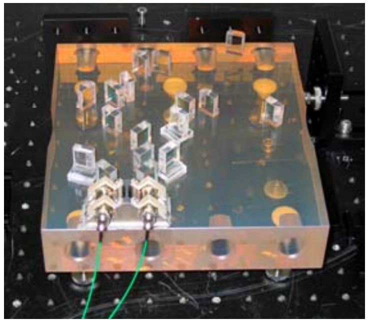
  - Micronewton thruster performance,
  - Spacecraft drag-free control to better than 10 nm/√Hz from 1 to 30 mHz,
  - LISA "short arm" optical performance.



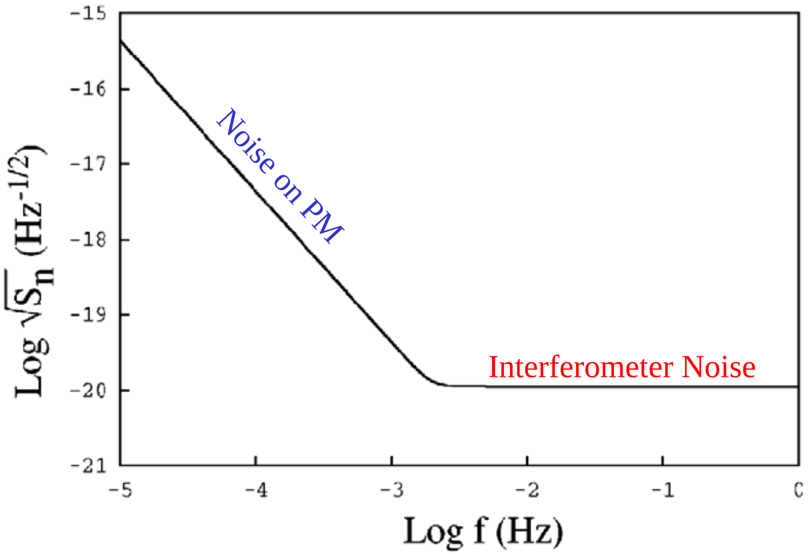


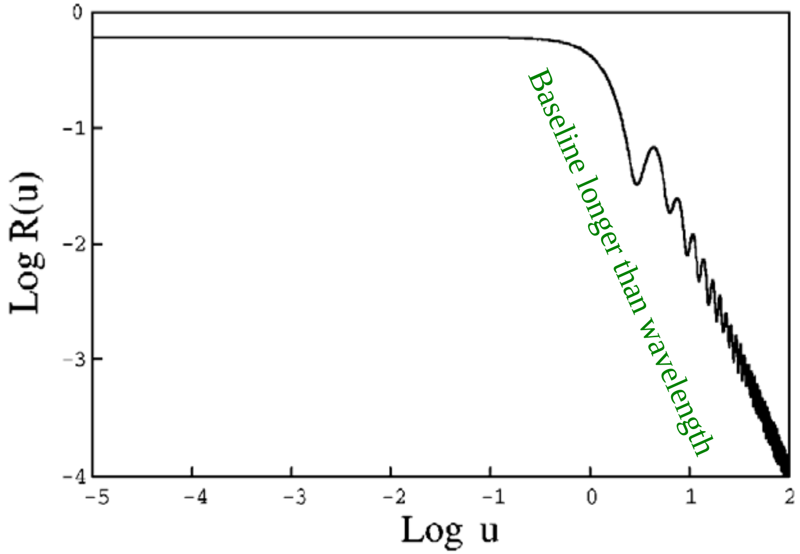


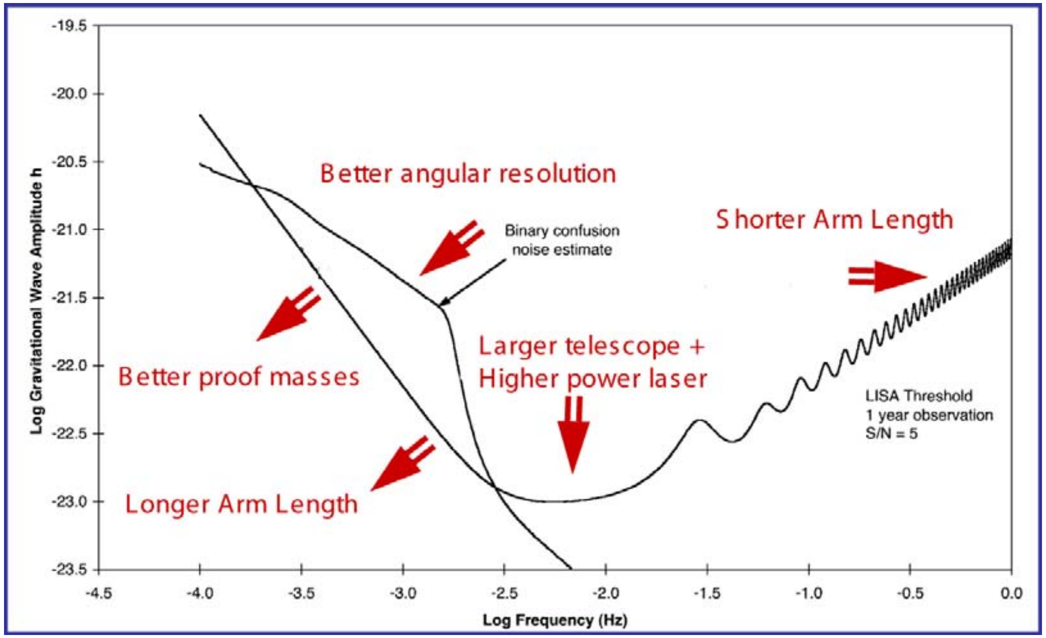




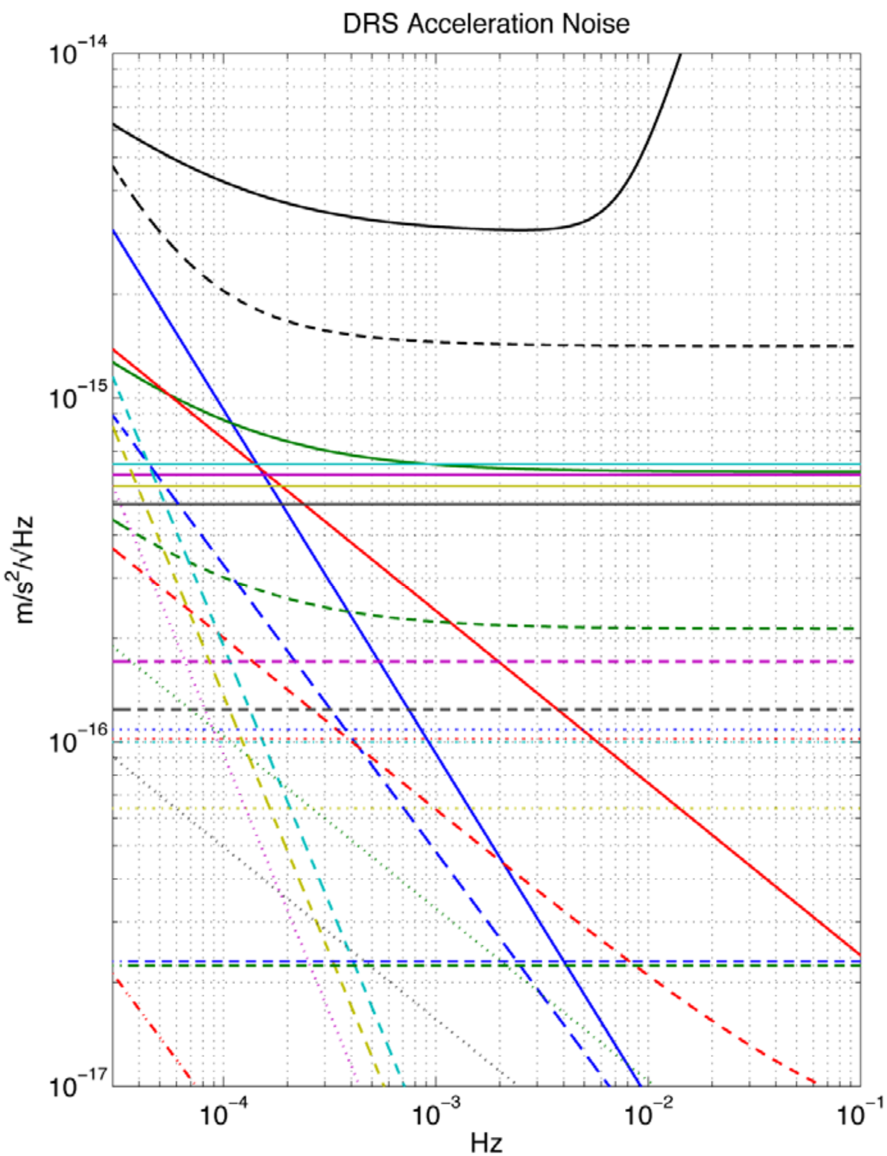
LISA Frequency Response







DRS Acceleration Noise Model

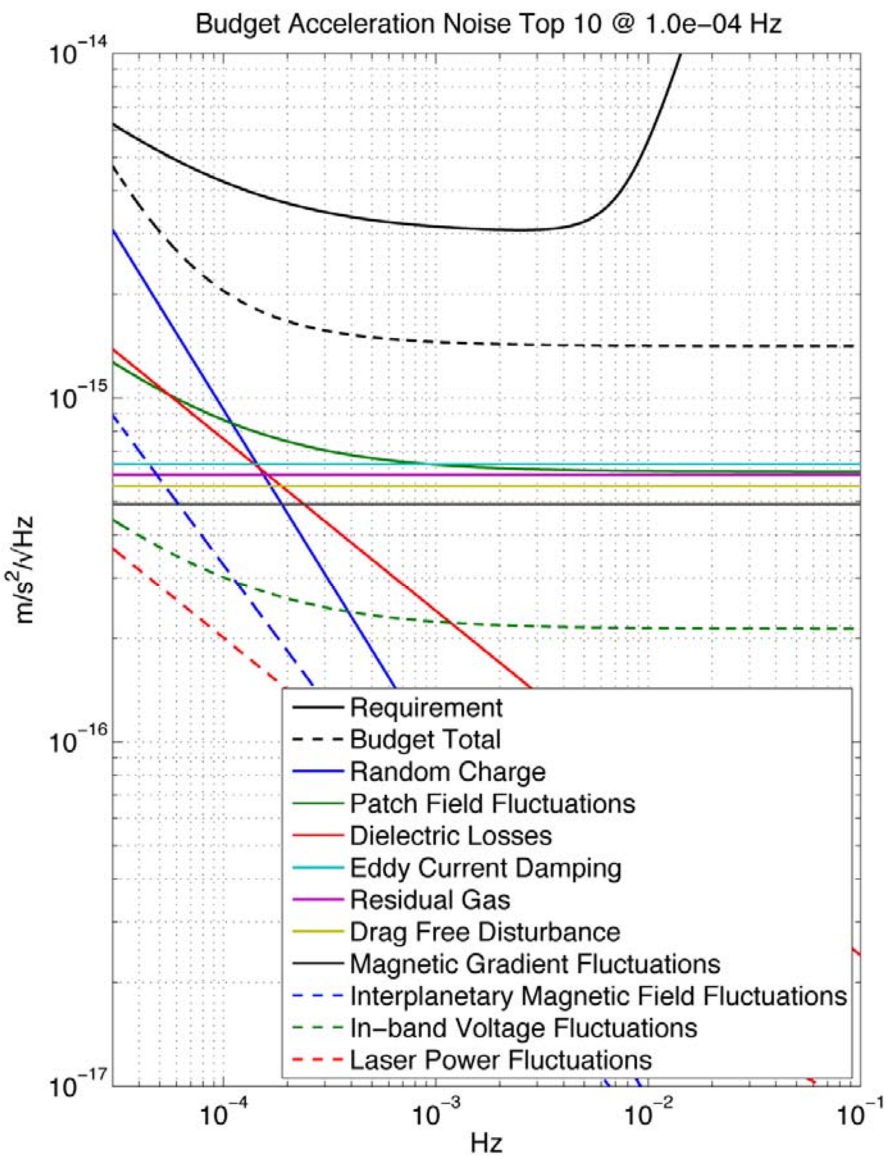


- Current DRS noise model includes 57 physical effects:
  - Steady state PM acceleration
  - Steady state PM torque
  - PM-S/C coupling (stiffness)
  - Direct PM acceleration noise
- 123 physical parameters tracked:
  - Budgeted/allocated
  - Current best estimate (CBE)
  - Demonstrated
  - Goal/optimistic

$$\sqrt{S_a} \le 3\times 10^{-15}\sqrt{1+\left(\frac{f}{8\,\mathrm{mHz}}\right)^4}\sqrt{1+\left(\frac{0.1\,\mathrm{mHz}}{f}\right)}\ \mathrm{m/s^2}/\sqrt{\mathrm{Hz}},$$

$$0.03\,\mathrm{mHz} \le f \le 100\,\mathrm{mHz}$$

DRS Noise Budget

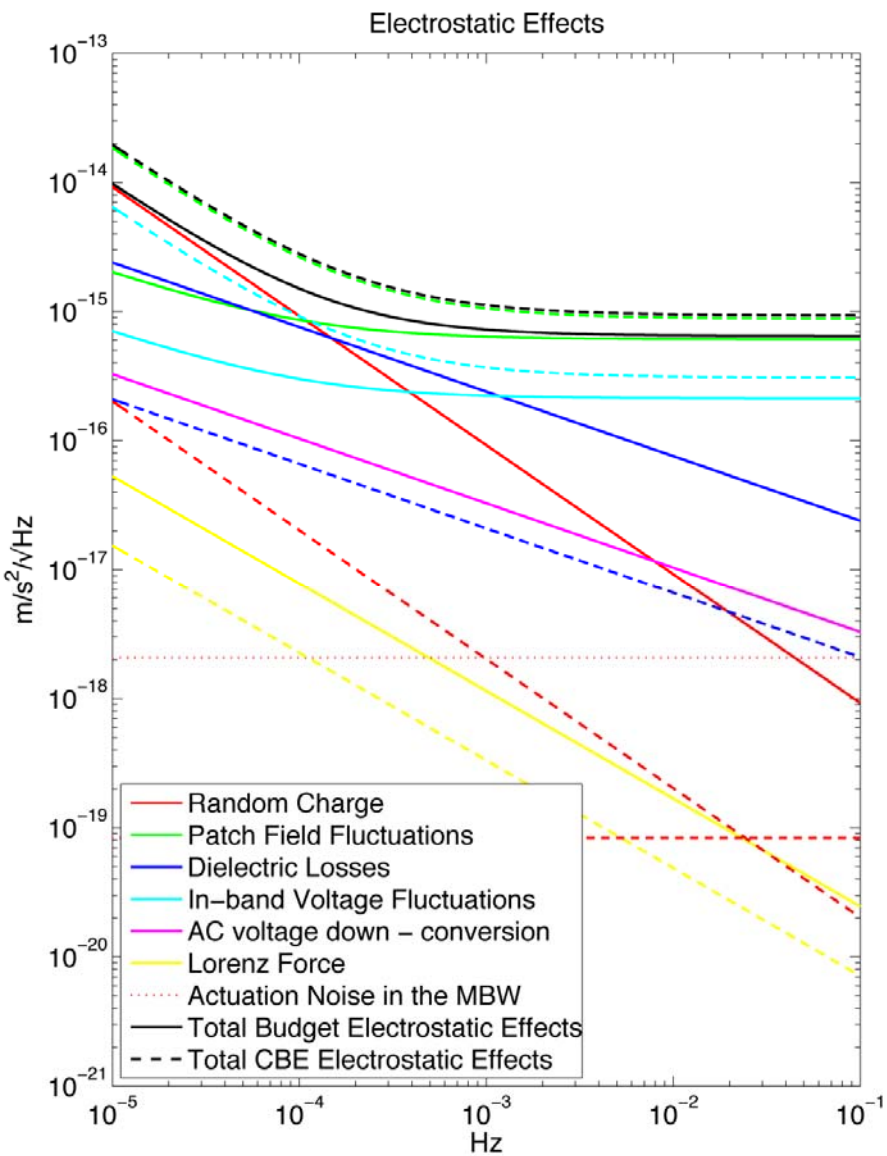


$$\sqrt{S_a} \le 3\times 10^{-15}\sqrt{1+\left(\frac{f}{8\,\mathrm{mHz}}\right)^4}\sqrt{1+\left(\frac{0.1\,\mathrm{mHz}}{f}\right)}\ \mathrm{m/s^2}/\sqrt{\mathrm{Hz}},$$

$$0.03\,\mathrm{mHz} \le f \le 100\,\mathrm{mHz}$$

Disturbance Group	Allocation ($\times10^{-16}(1+(f/8\mathrm{mHz})^4)^{1/2}$ m/s²/ĆHz)
Electrostatics	13.6
Magnetic	9.5
Spacecraft Coupling	6.5
Thermal	4.5
Miscellaneous Small Effects	6.5
Total (Quadrature)	19.5
Reserve/Contingency (Linear)	10.5
Required Total	30.0

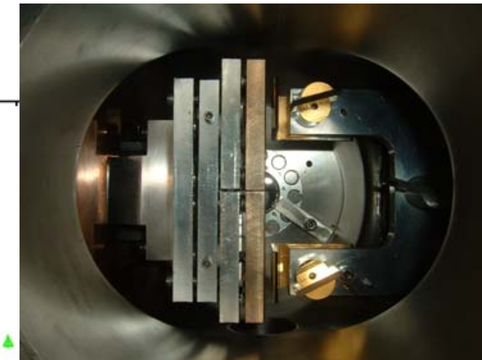
Electrostatic Effects

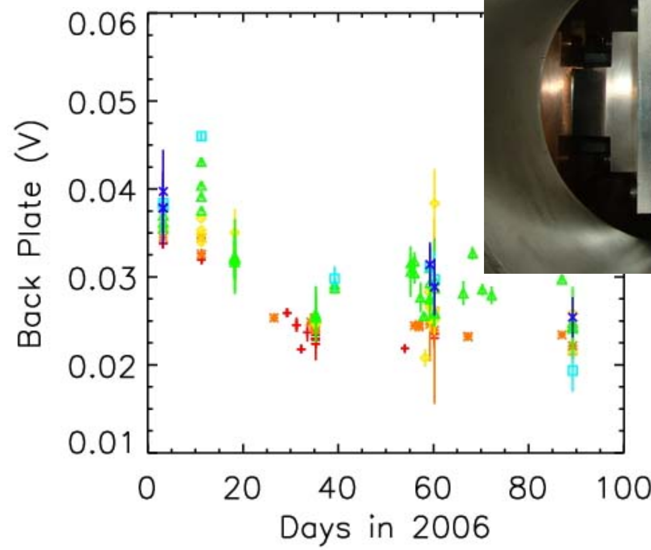


- Random Charge
  - Fluctuating PM charge coupled to DC field.
- Voltage Fluctuations
  - In-band fluctuating stray voltages coupled to PM charge and stray DC field.
- Dielectric Losses
  - Thermal noise from lossy capacitors.
- DC Voltage Stiffness
  - PM electrostatic coupling to S/C motion.

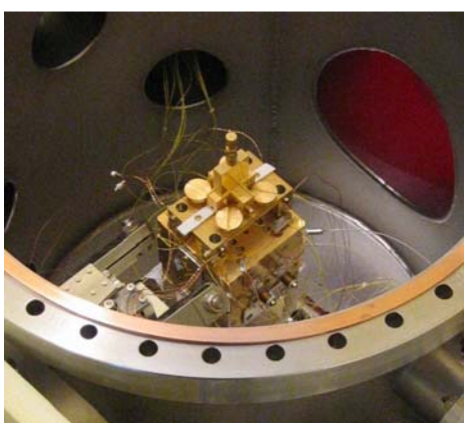
Stray DC Potential

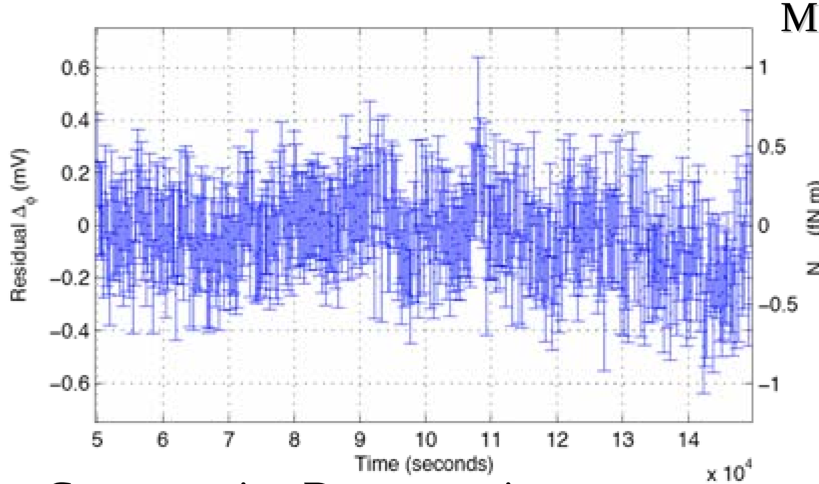
- Spatial average of voltage difference from opposite faces.
- Mostly from 'large' patches of spatially varying surface potentials.
- Can be partially compensated by carefully applied electrode voltages.
- Measurements at UW and Trento confirm stray DC voltage of ~50 mV.
- Measurements at Trento demonstrate compensation to ~0.5 mV.





UW Small Force Measurements

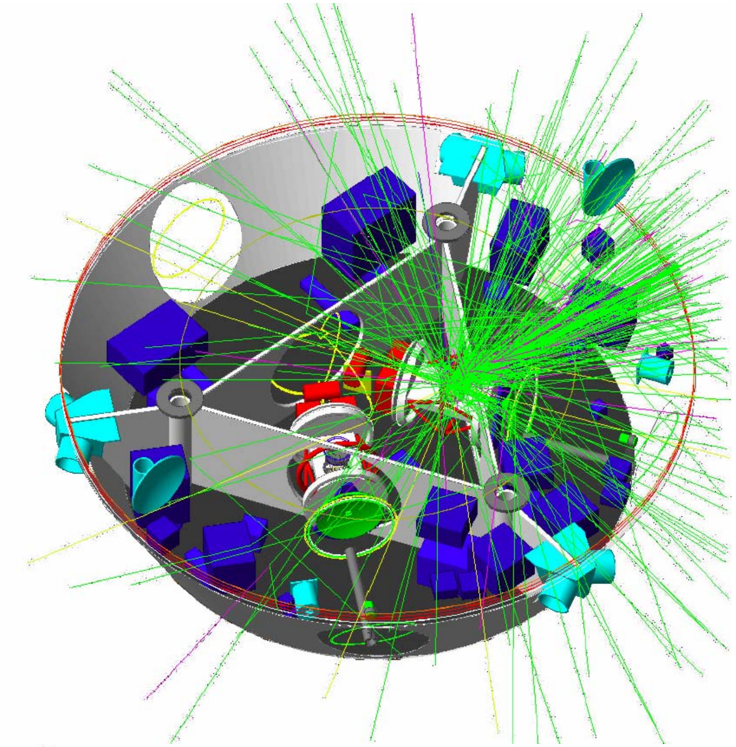


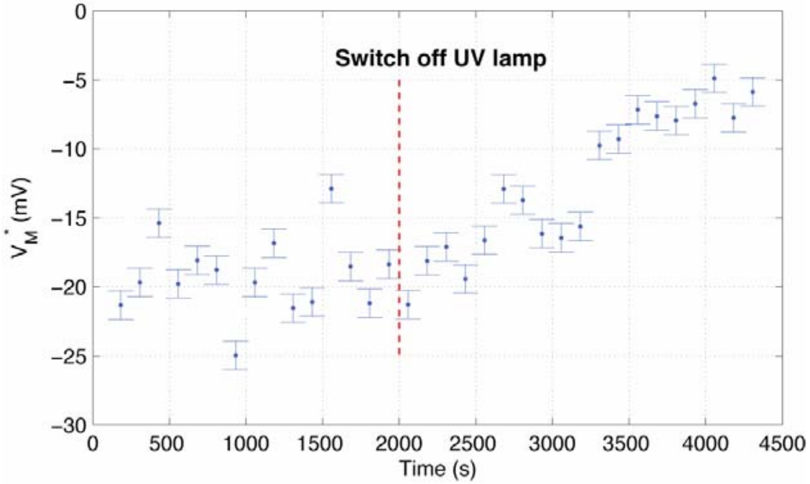


Trento Voltage Compensation Demonstration

Proof Mass Charge

- Cosmic ray impacts will charge the PM.
- Total charge and charge fluctuations will couple to the DC field causing spurious accelerations.
- Charge fluctuations are $\propto$ to the charging rate:
  - Imperial College GEANT4 model predicts charging rate of < 50 e/s.
  - INFN Fluka model predicts charging rate of 150 e/s.
  - Charging rate on GP-B was 8 e/s (Imperial College predicted 12.5 e/s GEANT4).
- Total charge controlled by shining UV light on PM and housing.
  - Measurements at Trento demonstrate charge reduction to ~5x10^{6}e (2x lower than budget).





Closed Loop Charge Control

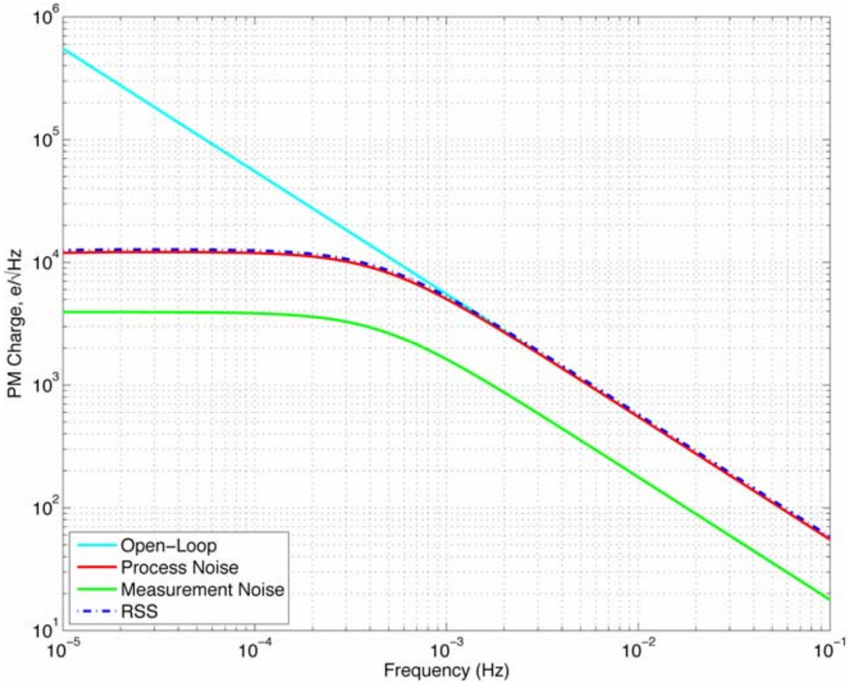
Beyond Einstein: From the Big Bang to Black Holes

- Charging rate related to charge noise:

$$\sqrt{S_q} = \frac{e\sqrt{2\lambda}}{2\pi f}$$

- Trento/Imperial measurements demonstrated that charge transfer rates of at least 7x10^{5}e/s are possible using UV system.
- GRS should have a charge measurement sensitivity of:

$$\delta q = 13000e\left(\frac{100\text{mV}}{V_\Delta}\right)\sqrt{\frac{3600\text{s}}{t}}\left(\frac{f_m}{1\text{mHz}}\right)^2\left(\frac{\sqrt{S_{x_n}}}{5\text{nm}/\sqrt{\text{Hz}}}\right)$$

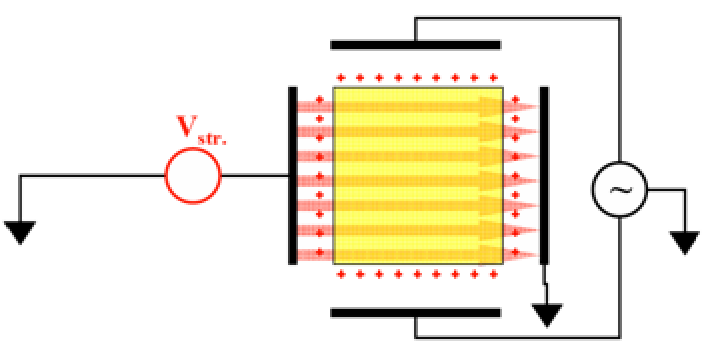


- Sampling the charge measurement every 3300s and assuming λ=600/s (double cosmic ray rate to account for UV shot noise) we constructed a simple PI controller.

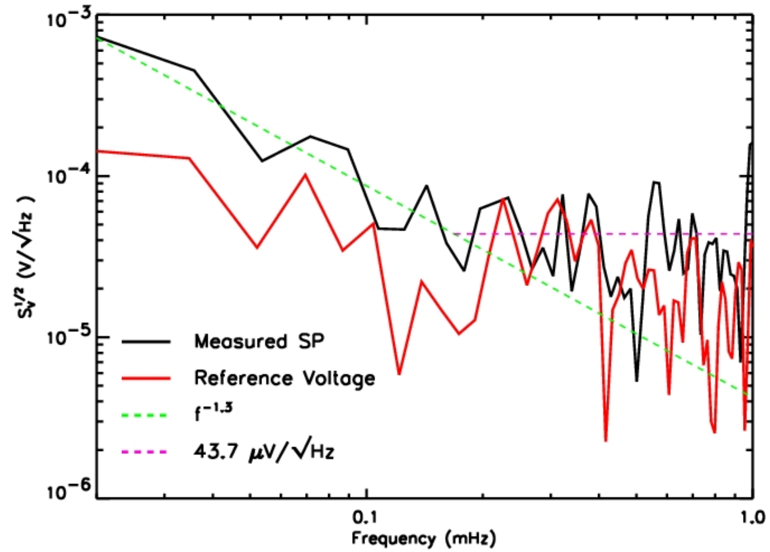
3σ charge on the PM is 10^{3}e (10^4 x lower than requirement)!

Voltage Fluctuations

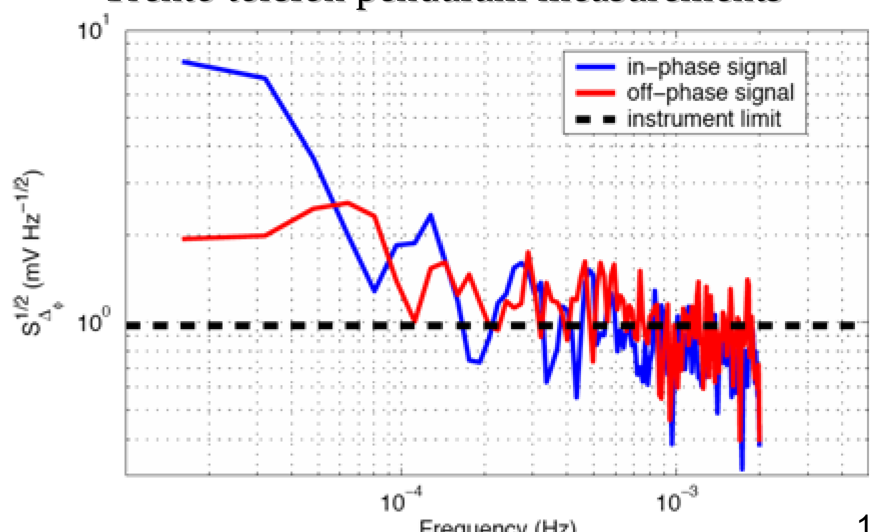
- DC field will fluctuate due to:
  - Changing patch fields,
  - Noise in applied voltages.
- Voltage fluctuations will couple to PM charge and stray DC potential:
  - Measurements at UW put upper limit at 44 μV/√Hz at 0.15mHz with $f^{-1.3}$ rise below, ~4.4x budget value.
  - Measurements at Trento put upper limit at ~1 mV/√Hz at 0.1mHz, ~100x budget value.
  - Measurements on GSFC Kelvin probe put upper limit at ~1 mV/√Hz at 0.4mHz.



UW torsion pendulum measurements

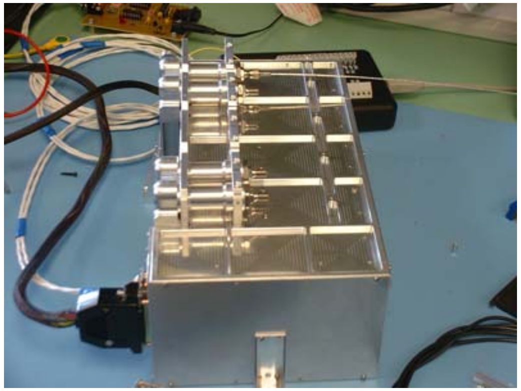


Trento torsion pendulum measurements



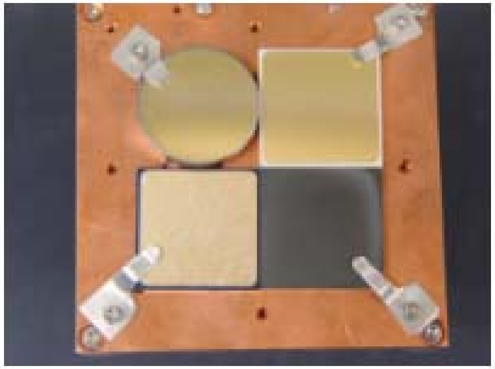
Achieving Electrostatic Performance

- Wide gap between PM and housing,
  - Major difference from GP-B and space accelerometers.
- No applied DC voltages along sensitive axis,
- Stray DC voltage active compensation,
- High quality surface coatings,
- High stability power supplies,
- Closed loop UV discharging of proof mass.



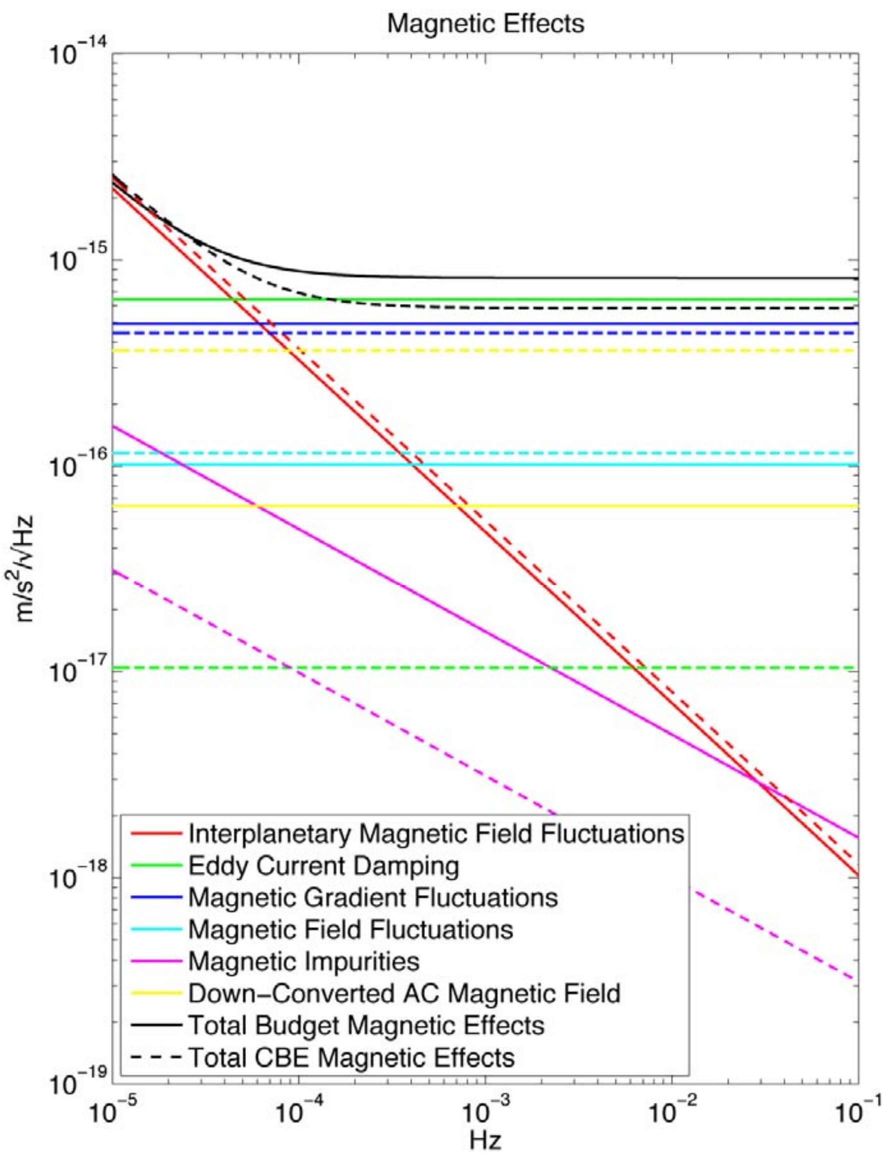
LTP UV Lamp

UW Small Force Pendulum



Material samples for Kelvin probe

Magnetic Effects

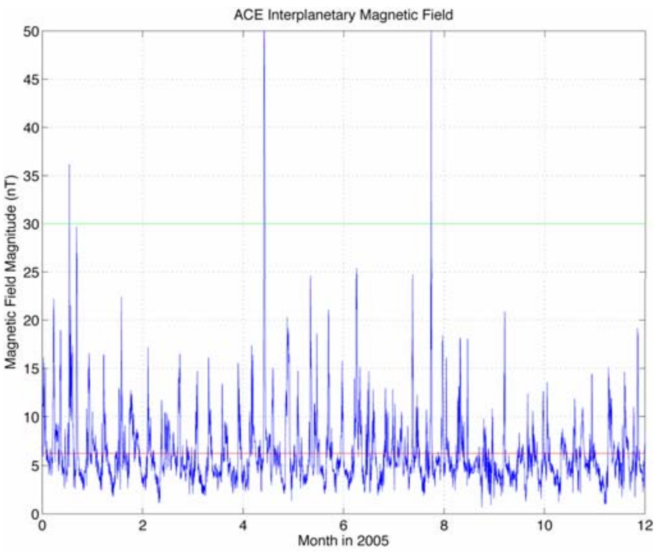


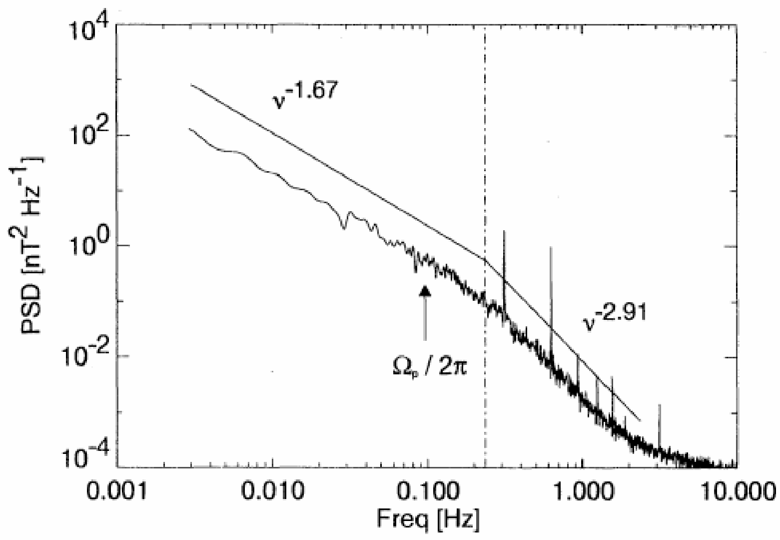
- Interplanetary magnetic field fluctuations:
  - Interaction between IP magnetic field with S/C magnetic gradient and PM magnetic susceptibility.
- Eddy current damping:
  - Fluctuations from magnetic gradient induced current dissipations.
- Magnetic gradient fluctuations:
  - Interaction between fluctuating S/C magnetic gradient and PM magnetic susceptibility and residual dipole moment.

Interplanetary Magnetic Field

- Good data exists on interplanetary magnetic field from ACE, Cluster, and other S/C.
- 2005 ACE MAG data has a mean of 6.3 ± 3.7 nT. The value currently assumed in the error budget is 30 nT, more than 6σ higher.
- The spectral behavior matches well classical Kolmogorov fluid turbulence, thus the power spectral density of the fluctuations will have an $f^{-5/3}$ behavior.
- Magnitude of the power spectrum varies considerably. Conservatively assume 320 nT/√Hz at 0.1 mHz.

$$\sqrt{S_{Bi}} = 320nT / \sqrt{Hz} \sqrt{\left(\frac{10^{-4}\,Hz}{f}\right)^{5/3} \frac{1}{1+\left(\frac{f}{0.44\,Hz}\right)^{3}}}$$





R. Leamon *et al.*, J. Geophys. Res. **104**, 22331 (1999).

S/C Magnetic Field

- Levels required by LISA are more than 10x easier than magnetically clean spacecraft.
- Magnetic gradients come mostly from:
  - Strong magnetic materials
  - Soft magnetic materials
  - Currents
- Magnetic zones can be set up to take advantage of r^4.

$$\mu = \frac{2\pi}{3\mu_0} r^4 \max\left(B_{xx}\right)$$

- $B_{xx}=1\times10^{-6}$ T/m is equivalent to 20 J/T dipole 1.86 m away.
- Current watch list meets requirements with modest shielding.

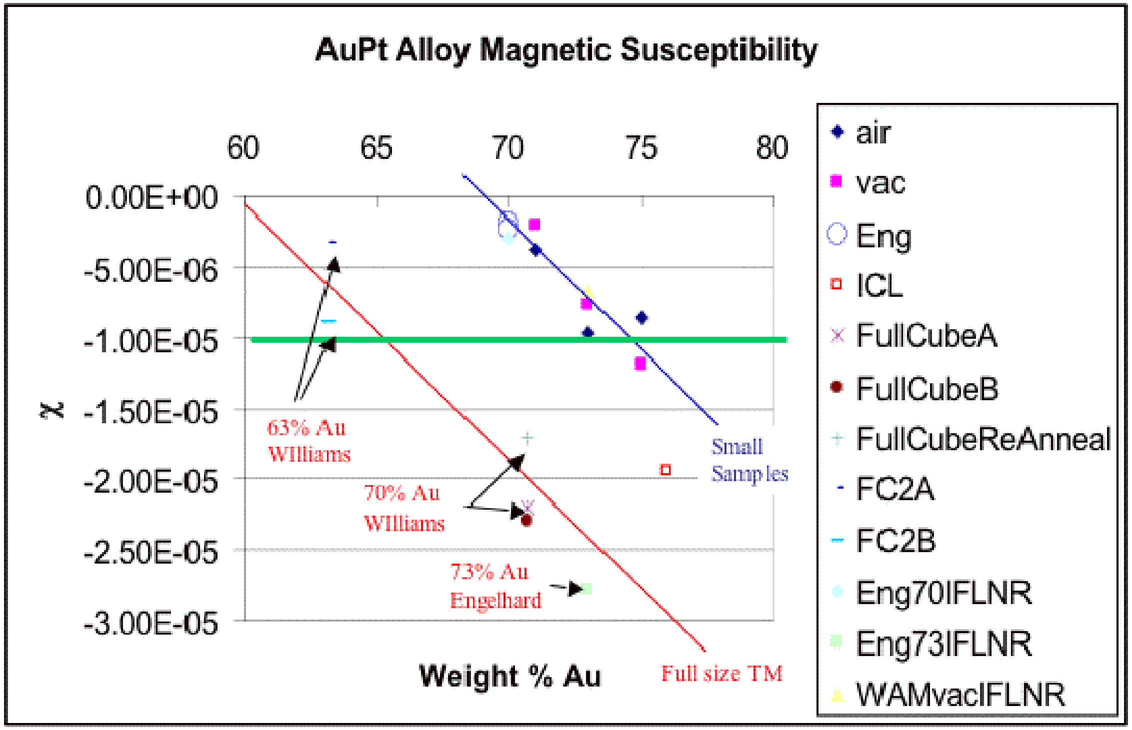
Component	Quantity	Dipole (J/T)
HGA Drive Mechanism	2	
Transponders	2	
RFDU	1	
Heaters	Many	
Solar Array	1	
Battery (9A/h LiIon)	1	
Power System Electronics	1	
Power Switching & Distribution Unit (PSDU)	1	
SSPA/TWTA	2	15
Lasers	4	
Isolator	4	10

Magnet Watch List

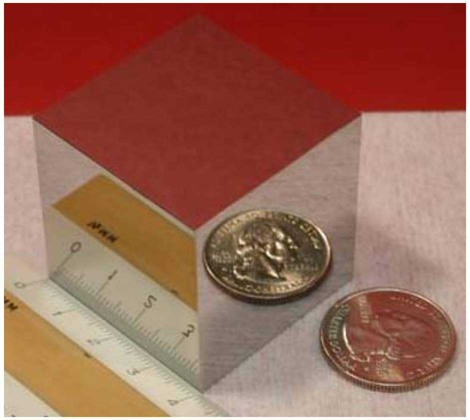
Zone	Name	Min PM Distance	Max Magnetic Dipole (A-m^2)
A	Proof masses	0	0
B	Proof mass housings	2	2.70E-12
C	Optical bench	44	6.20E-07
D	Telescope assembly	222	4.00E-04
E	Y-tube outer surface	225	4.30E-04
F	Outside the Y-tube, beyond 250 mm	250	6.50E-04
G	Outside the Y-tube, beyond 500 mm	500	1.00E-02
H	High Gain Antennas	936	1.30E-01
I	Solar array	200	2.70E-04

Magnetic Zones

Proof Mass Magnetic Properties

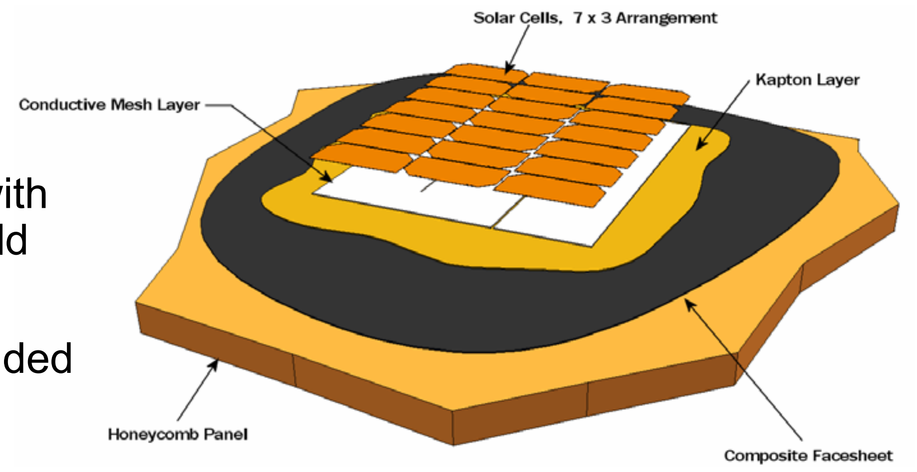


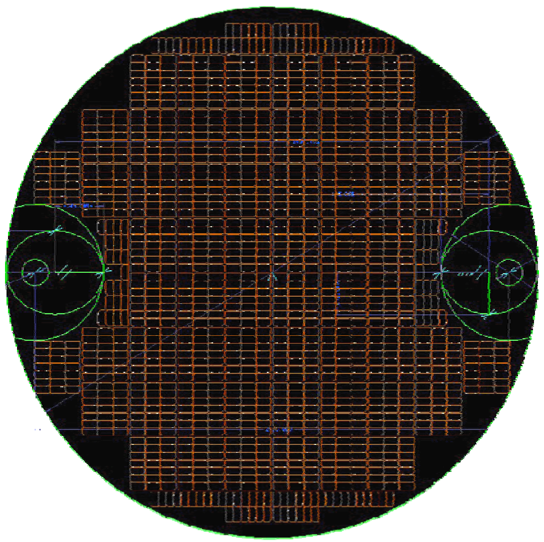
- From Stanford measurements we find that a magnetic susceptibility of 1.7×10^{-5} is achievable in a full scale PM.
- Full sized sample had a magnetic moment of ≤ 12 nA m^2.
  - ≤ 20 nA m^2 required.



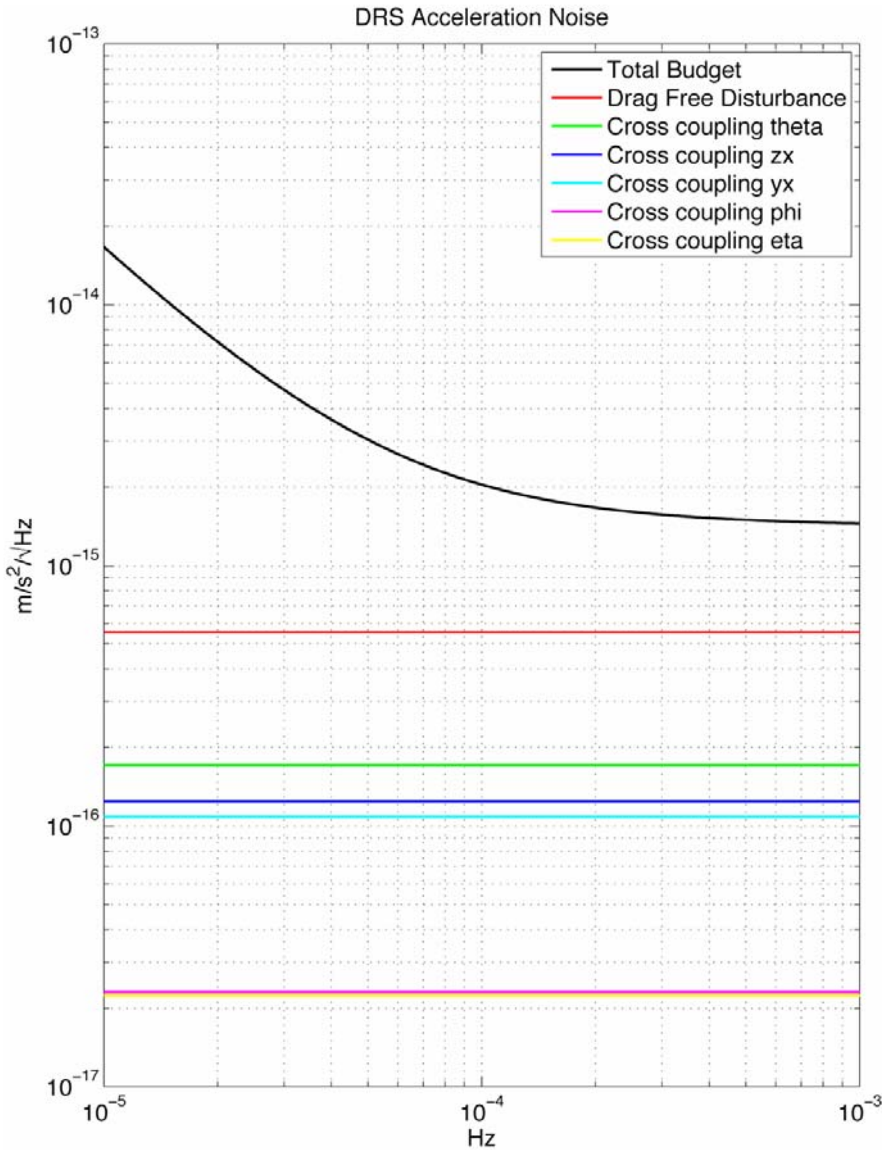
Achieving Magnetic Performance

- Minimize PM magnetic properties.
- Minimize use of magnetic material.
- Permanent magnets can be compensated with oppositely oriented duplicate such as the cold spare.
- Remaining permanent magnets can be shielded with METGLAS (Metglas Solutions, Inc) or VITROVAC (Vacuumschmeltze).
- Backwire solar array.
- Use twisted pair for all wiring.
- Eliminate current loops in power system using star or single point grounding.
- No primary supply currents should be allowed to flow through the spacecraft structure.
- Small thermal gradients.





Spacecraft - PM Coupling

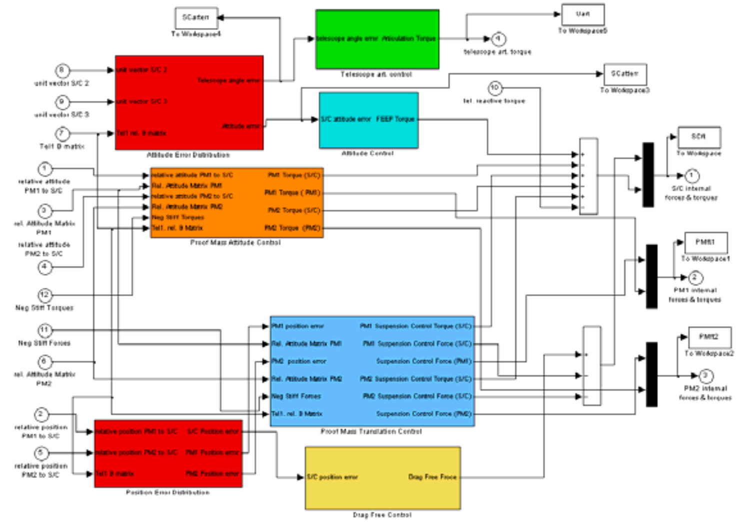


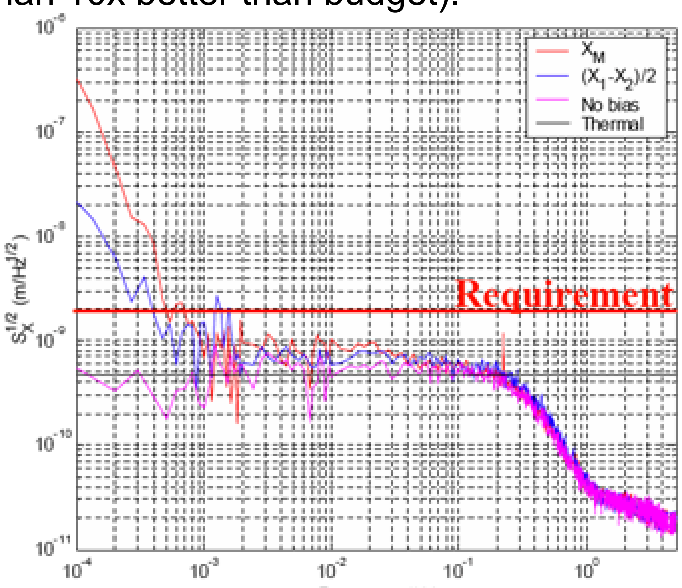
- Residual S/C motion will couple to PM through stiffness.
- Off-diagonal stiffness terms will cross-couple S/C motion to sensitive axis.
- Self-gravity gradient dominates stiffness budget.

Description	Budget (s^{-2})
Self-Gravity Gradient	1.00E-07
Sensing Stiffness	4.34E-08
Rotation Actuation Stiffness	1.64E-08
Magnetic Stiffness	1.18E-08
DC Voltage Stiffness	3.59E-09

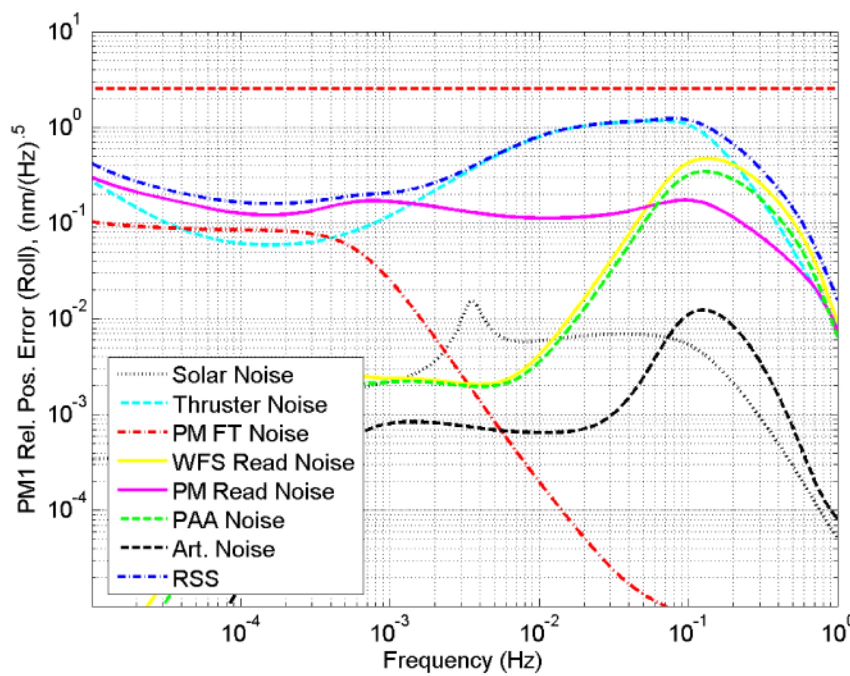
Control Law Performance

- DRS controls S/C (6-DOF), two Proof Masses (6-DOF each), and telescope articulation for total of 19-DOF.
- Three S/C combined gives 57-DOF, but control is local to one S/C.
- Nonlinear translational and rotational kinematics and dynamics.
- Preliminary designs completed for all DRS control systems.
- Control is straightforward and simulations predicts position control 0.18 nm/√Hz @ 0.1 mHz (more than 10x better than budget).



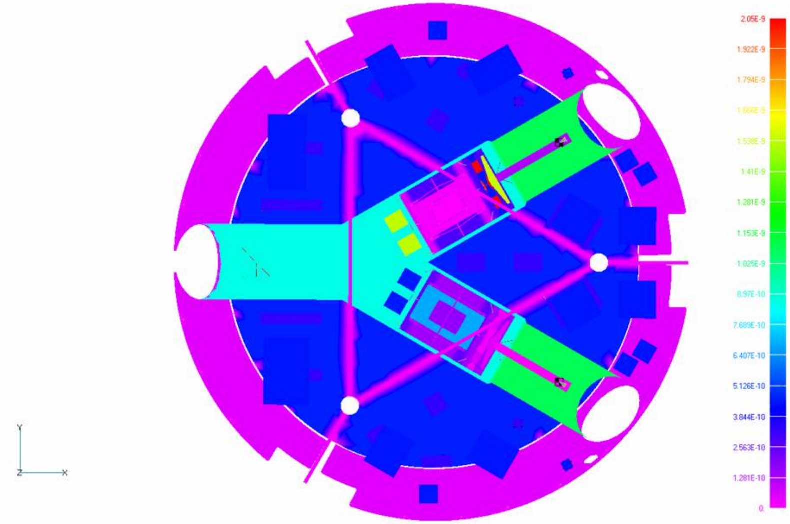


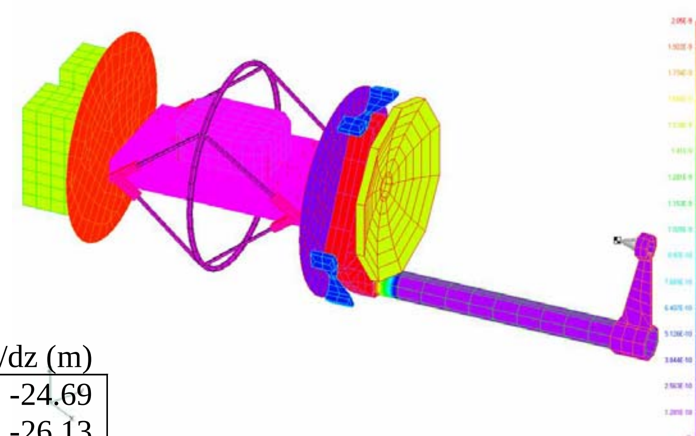
LTP Prototype Sensor Noise Measurements



Self-Gravity Gradient

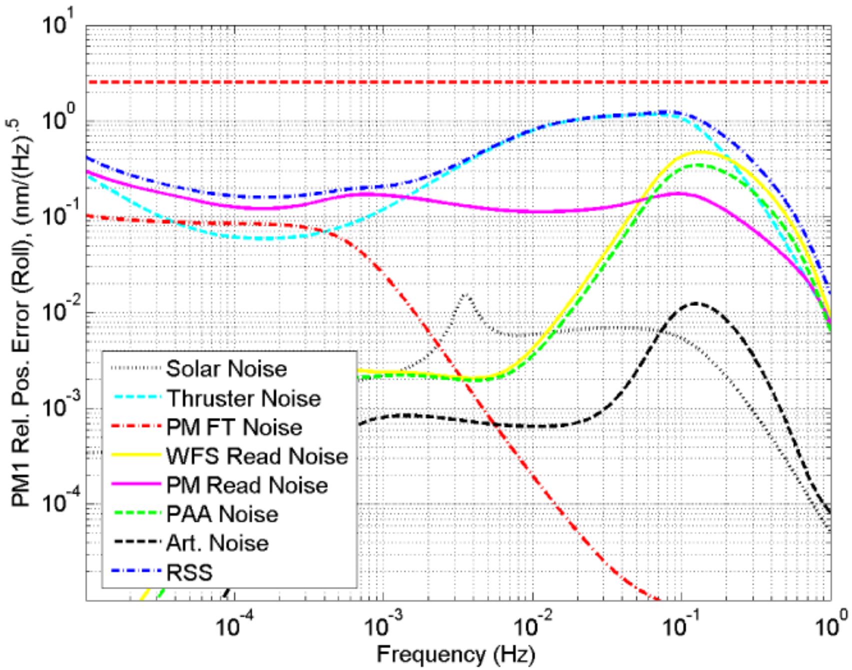
- Self-gravity gradient is the dominant stiffness term.
- Self-gravity tool developed to aid in design and verification.
- Analysis of unoptimized design within 4x of budget.
- Field can be compensated for by strategically placed masses.

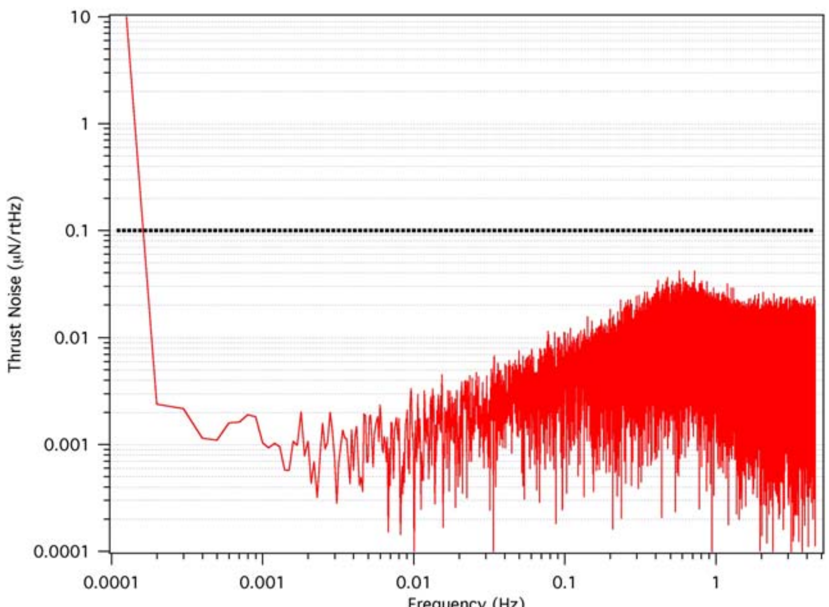


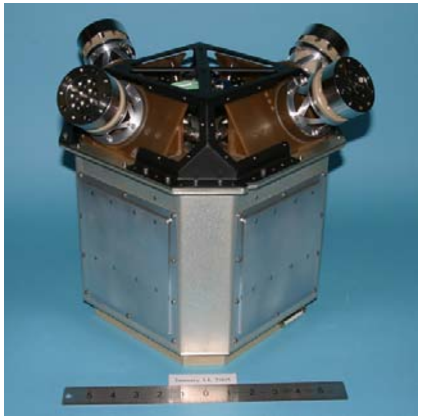


	/dx (m)	/dy (m)	/dz (m)	/dx (m)	/dy (m)	/dz (m)
dAx $(1/s^2 \times 10^{-10})$ =	-1264.32	85.39	-25.74	-1258.04	-104.25	-24.69
dAy $(1/s^2 \times 10^{-10})$ =	85.39	1669.91	7.20	-104.25	1666.05	-26.13
dAz $(1/s^2 \times 10^{-10})$ =	-25.74	7.19	-405.60	-24.69	-26.13	-408.01
dαx $(r/s^2/m \times 10^{-10})$ =	1.81	1137.84	49.92	1.42	1138.13	50.69
dαy $(r/s^2/m \times 10^{-10})$ =	-300.77	-0.70	-9.01	-300.88	-0.45	-6.62
dαz $(r/s^2/m \times 10^{-10})$ =	-1.73	-8.19	-1.11	-0.16	-4.63	-0.97

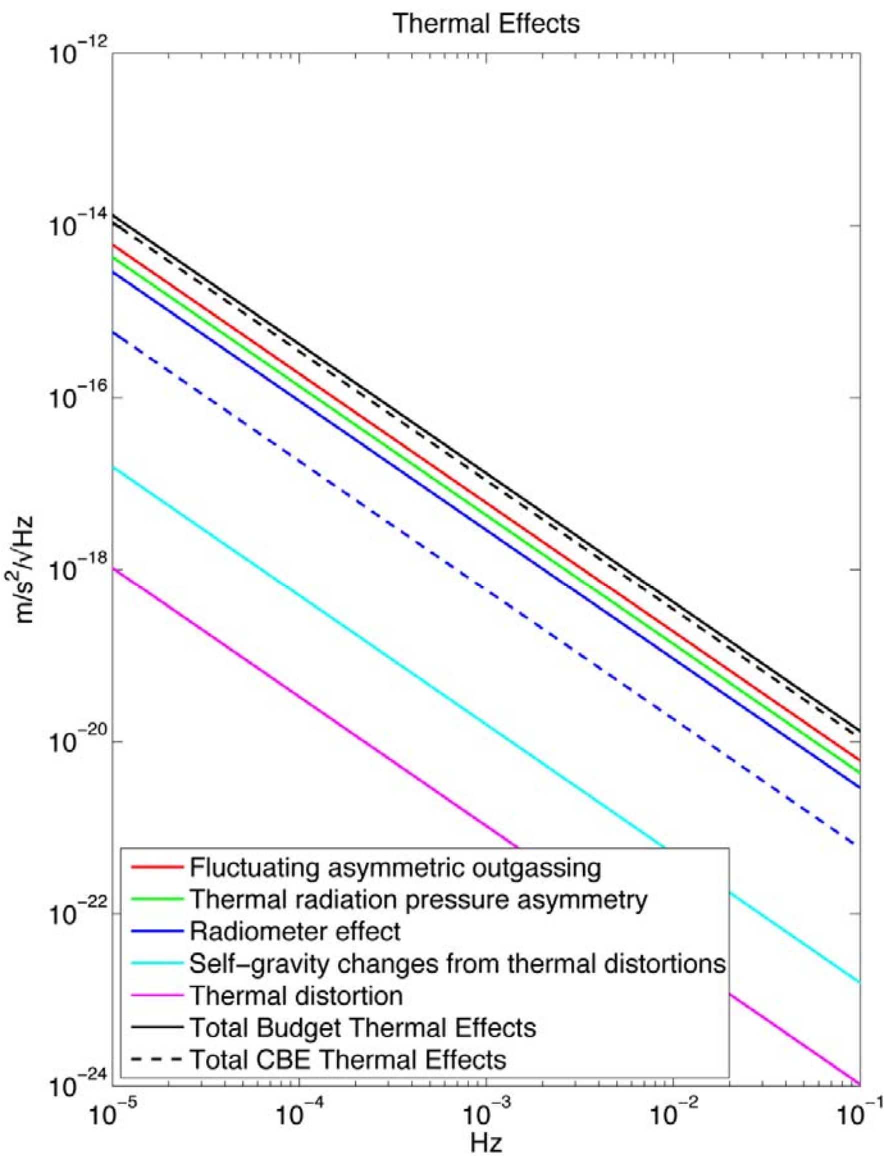
- Improve sensor sensitivity
- Use low-noise thrusters
- Careful tracking of all sciencecraft mass.



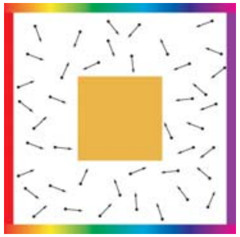




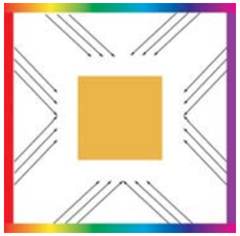
Thermal Effects



- Fluctuating asymmetric outgassing
  - Fluctuating pressure due to temperature dependent outgassing



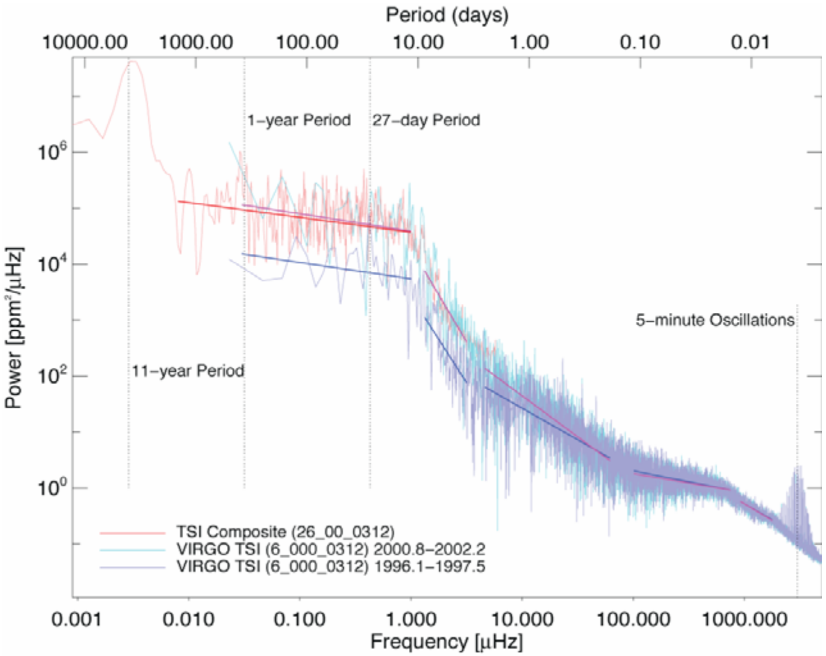
- Radiometer effect
  - Fluctuating temperature gradient of residual gas



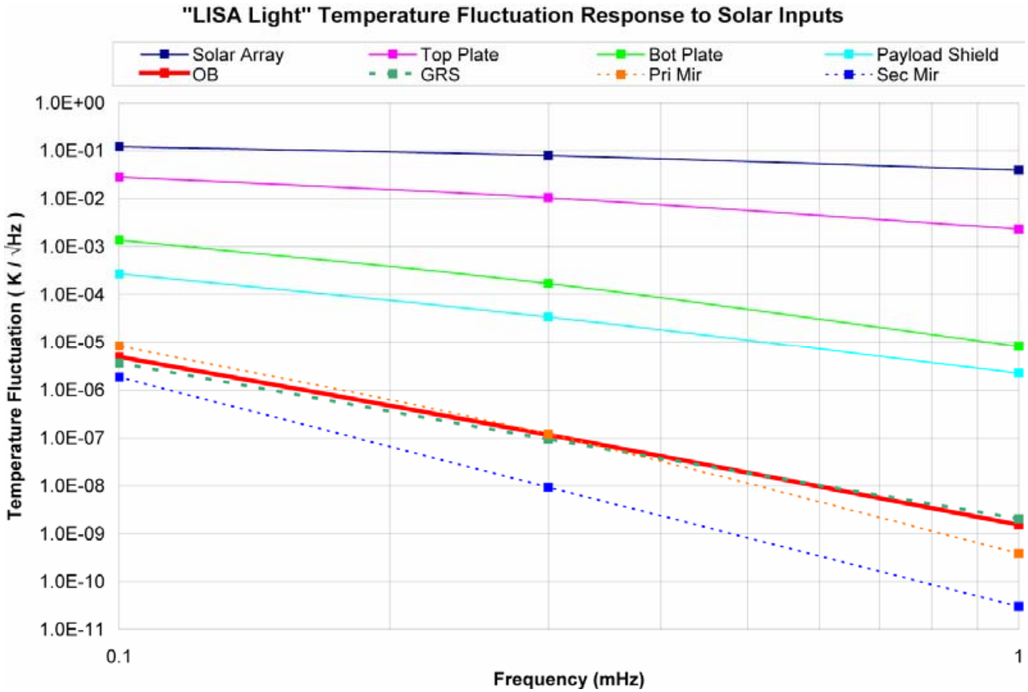
- Thermal radiation pressure asymmetry
  - Fluctuating blackbody radiation from EH
- Thermal distortion
  - Housing distortion that couple to PM through self-gravity and capacitance changes.

Thermal Stability

- Thermal fluctuations come from solar input and electronics.
- Current S/C design has several layers of thermal isolation.
- Thermal modeling indicates 10 μK/√Hz at 0.1 mHz feasible at GRS.

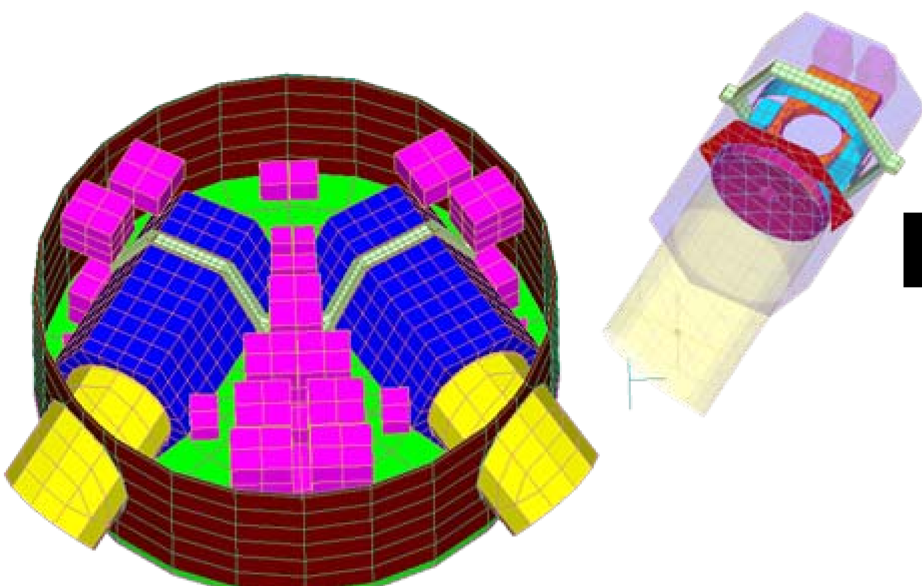


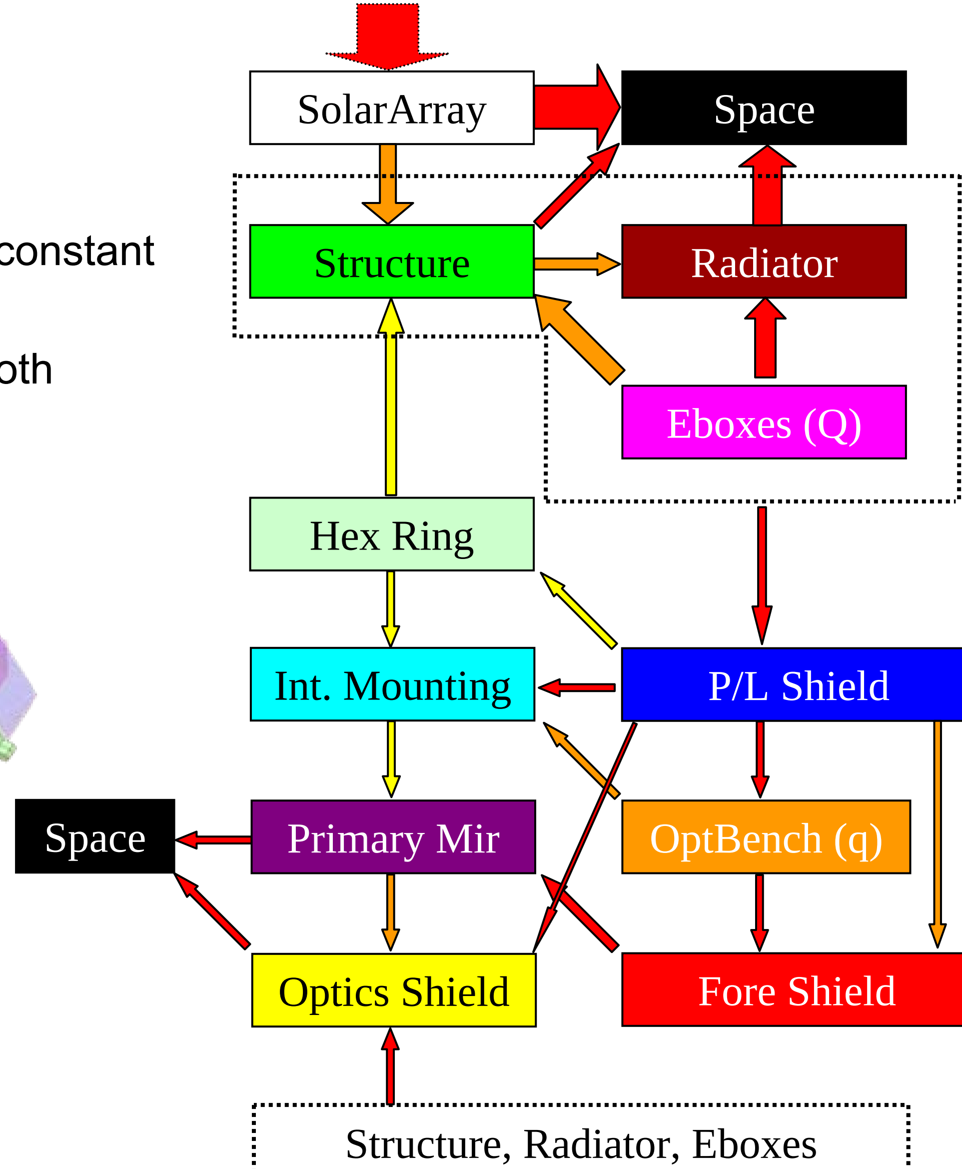
C. Fröhlich and J. Lean, Astron. Astrophys. Rev. **12**, 273 (2004).



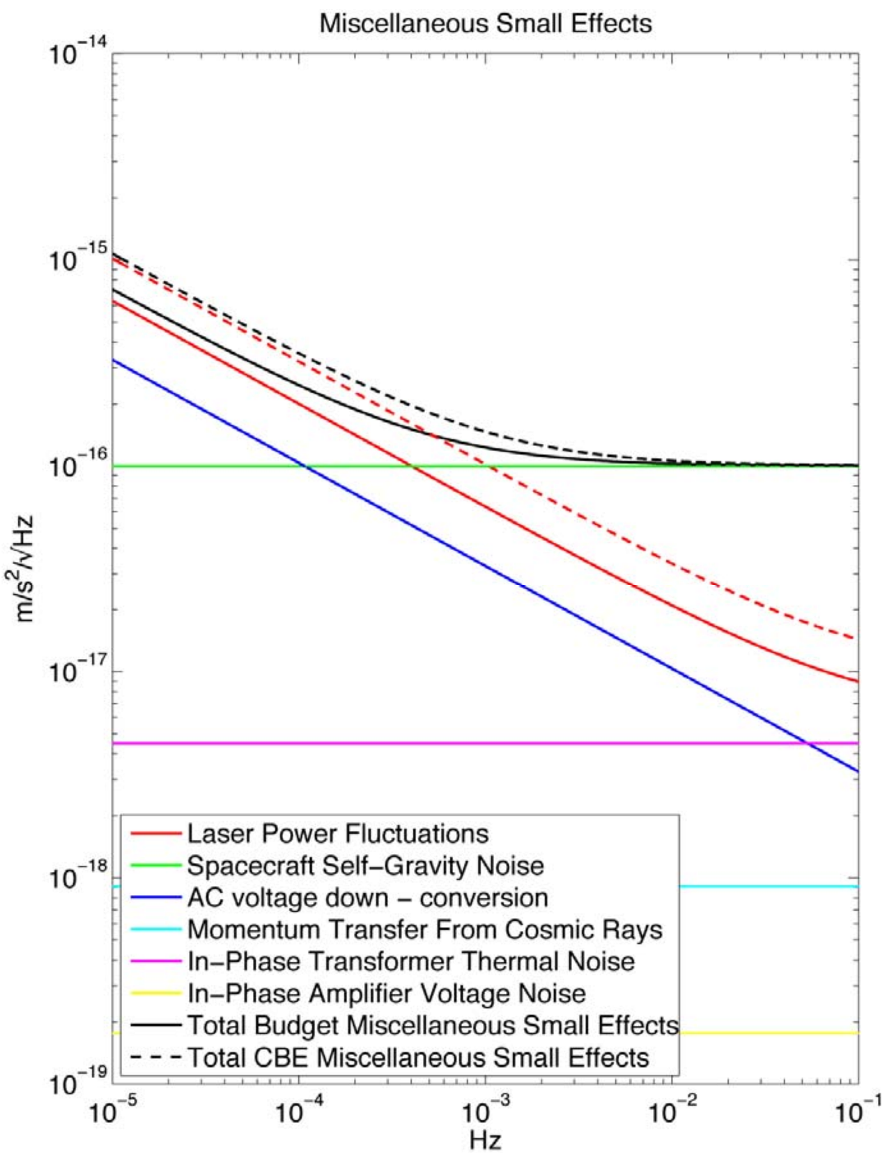
Achieving Thermal Performance

- Thermally stable environment
  - Constant orientation to sun,
  - Zero Earth/Albedo
- Power Stabilized electrical components (constant dissipation),
- Descending layers of thermal isolation, both conductive and radiative,
- Thermally conductive electrode housing,
- High vacuum.





Miscellaneous Small Effects



- Laser Power Fluctuations
  - Power stabilized lasers
- Spacecraft Self-Gravity Noise
  - Ultra-stable structures
  - Stable thermal environment
  - Minimize moving parts
- Residual Gas
  - Good vacuum around PM

Summary

- The low end of the LISA frequency band has the potential for exciting science.
- Pushing the low-frequency sensitivity will increase the precision of locating a source on the sky for follow-up observations.
  - LISA will measure the absolute distance and an electromagnetic identification of the source measures the redshift enabling us to map dark energy very far back in time with almost no interpretation problems.
- Many design options are available to improve low-frequency performance.
- Greatest challenge at low-frequency is verification of performance on-ground. Reliance on modeling may be heavy.