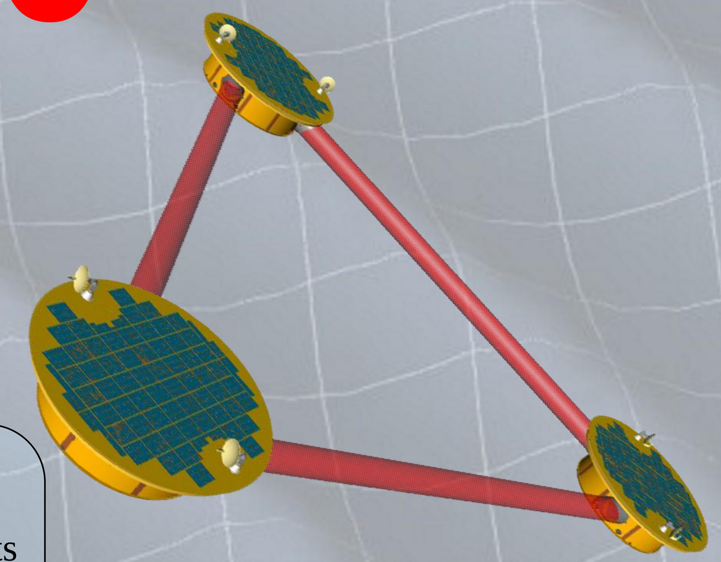
LISA Instrument Performance



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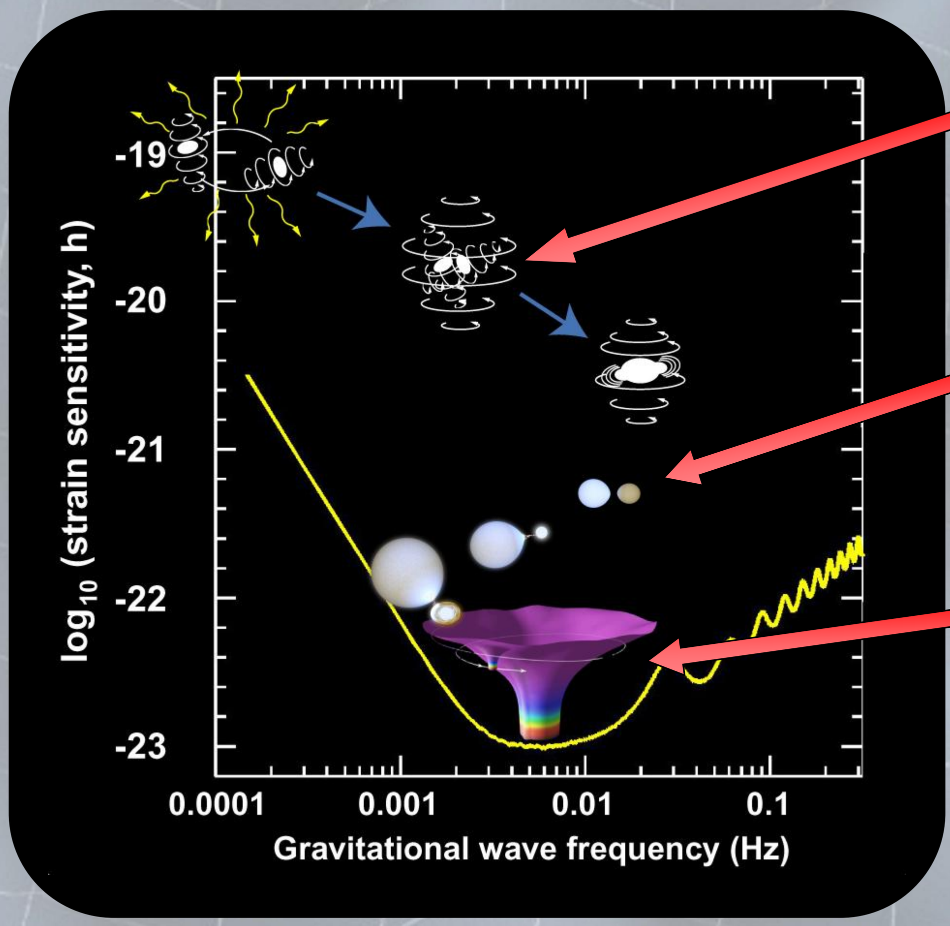
Abstract

LISA is designed to observe gravitational waves in the frequency band from 10^{-1} to 10^{-4} Hz, where a rich spectrum of sources is expected. The measurements must be made from space to avoid the large motions of the earth that prevent the current generation of detectors (e.g. LIGO) from operating at these frequencies. The technology and expected performance behind this measurement capability will be reviewed with an emphasis on the interferometric measurement system, including recent laboratory results showing a novel tunable frequency-stabilized laser.

The Science



Supermassive Black Hole Mergers

- Formation and growth of massive black holes
- Dynamical strong-field gravity
- Merger rates of 10s-100s yr^{-1} expected

Galactic close compact binaries

- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- $>10^4$ sources observed continually

Extreme Mass Ratio Inspirals (EMRIs)

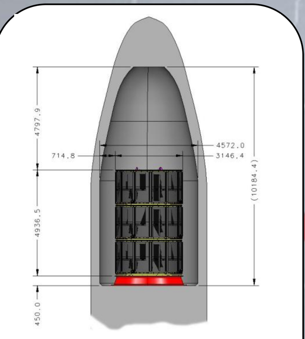
- Precision tests of GR in strong-field regime
- Event rates uncertain

New Physics / Unexpected Sources

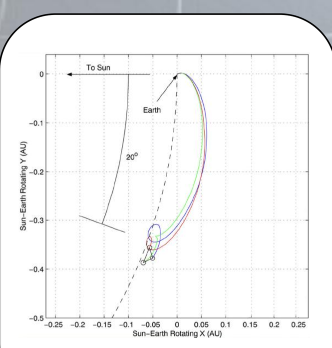
- Cosmological gravitational wave background
- Superstring bursts

Mission Overview

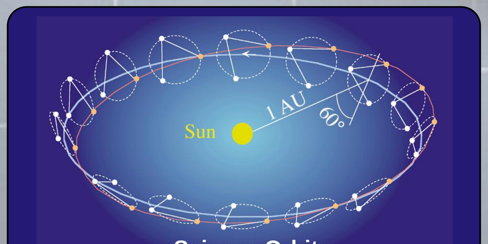
- Three spacecraft form a triangular constellation, 5 million km on a side
- Center of constellation in heliocentric orbit separated in orbital phase from Earth by 20º
- Each spacecraft contains freely-floating proof masses which act as inertial test masses
- Laser interferometry used to measure distance between proof masses



Stack in Atlas 5 m PLF

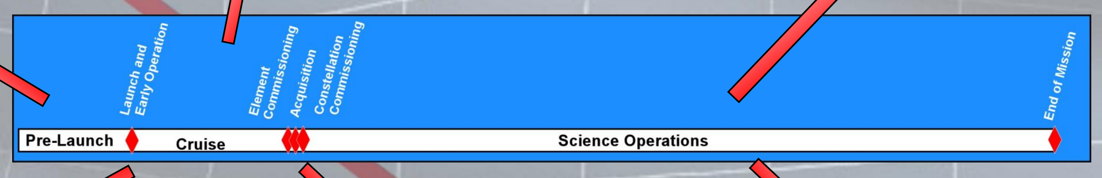


Cruise Trajectories

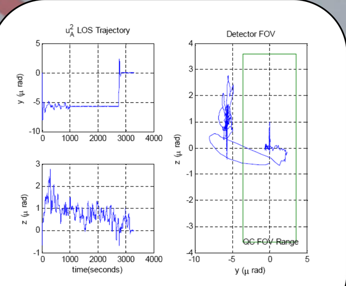


Science Orbits

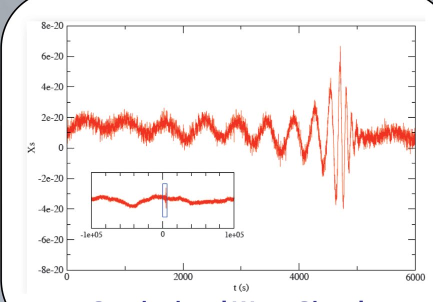
Mission Timeline



Atlas 531 EELV

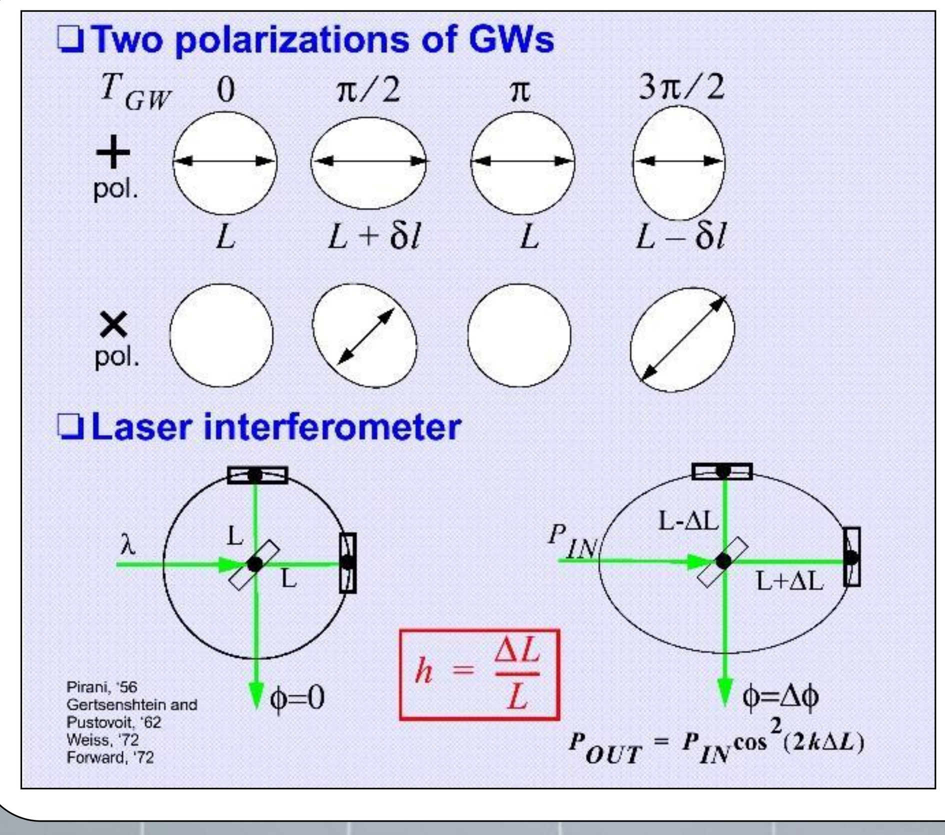


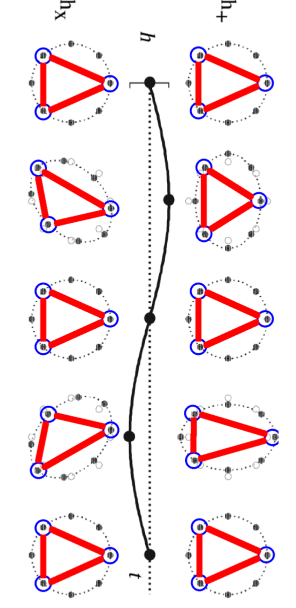
Constellation Acquisition



Gravitational Wave Signals

The Measurement Principle



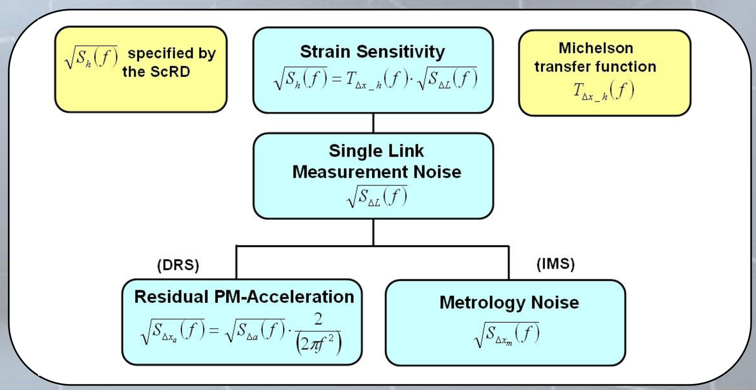


Response (exaggerated) of LISA Constellation

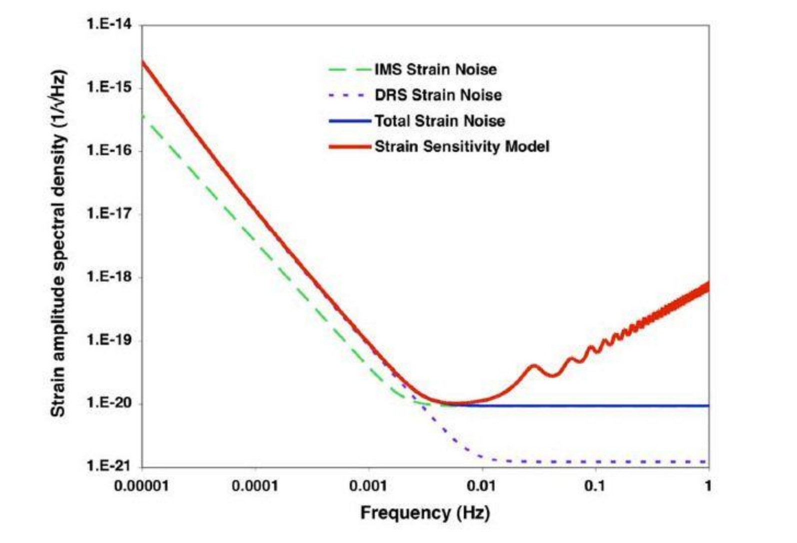
- Goal: Sense gravitational-wave induced tidal strains in the LISA constellation to $\sim 10^{-21}$
- Measurement is divided into two main tasks:
  - Provide good inertial reference frame for proof masses – *Disturbance Reduction System (DRS)*
  - Measure changes between proof masses – *Interferometric Measurement System (IMS)*

Noise Model/Requirements Flowdown

- The Instrument Sensitivity Model is a combination of
  - Displacement noise from the IMS
  - Acceleration noise from the DRS
  - Arm Length (5x10^6 km)
- The arm length also determines the instrument transfer function
- The requirements for the DRS and IMS are then suballocated.



High Level LISA Noise Model



Disturbance Reduction System (DRS)

- Goal: Isolate the proof-masses from external forces which would mask gravitational-wave signals
- Requires reducing residual acceleration to ~10^{-15} m/s²/√Hz
- Accomplished using *Drag Free Control*:
  - External forces acting on the spacecraft are sensed by a free-floating proof mass
  - Thrusters on the spacecraft are used to compensate the acceleration of the spacecraft

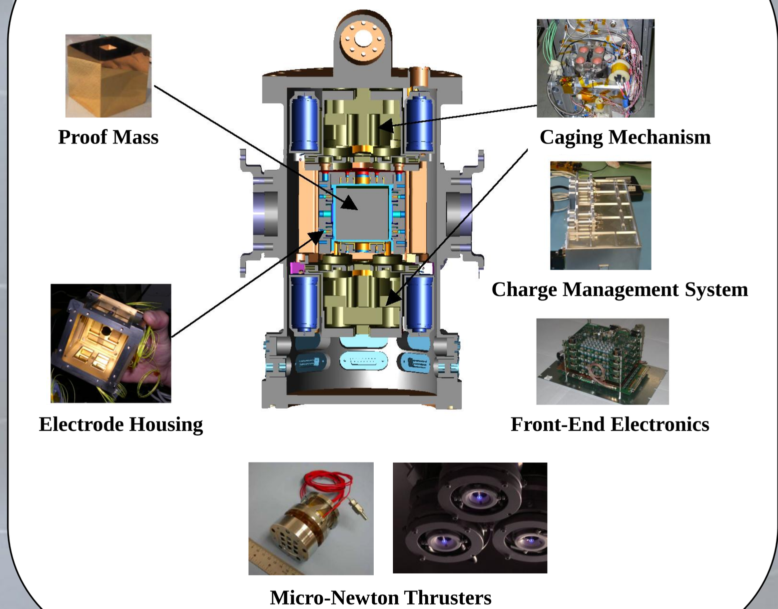
High Level DRS Error Budget

$\times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1+\left(\frac{f}{8\,mHz}\right)^4} \sqrt{1+\left(\frac{0.1mHz}{f}\right)}$

Effect	Total per group	Per group	Comments
Total Acceleration noise	**30.0**		
Contingency (35%)	**10.5**		Held by System Engineering
To be allocated (linear subtract)	**19.5**		RSS of sub-allocations
Disturbance Groups			
Electrostatics		12.0	
Brownian		9.1	
Spacecraft magnetic		7.0	
Spacecraft coupling		6.0	
Spacecraft cross coupling		4.5	
Thermal		4.0	
Interplanetary Magnetic		4.0	
Misc small effects		4.0	

A detailed error budget specifies the requirements on various components of the DRS. The allocations are specified in terms of acceleration noise.

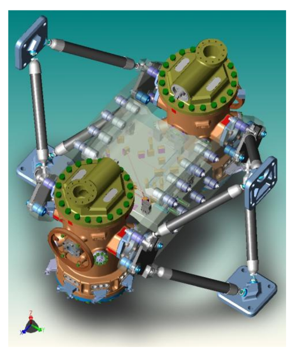
DRS Components



Development and testing of the DRS components is underway in various institutions worldwide. System-level tests are made on the ground using proof-masses suspended from torsion pendula. LISA Pathfinder will provide an on-orbit demonstration of the DRS technology.

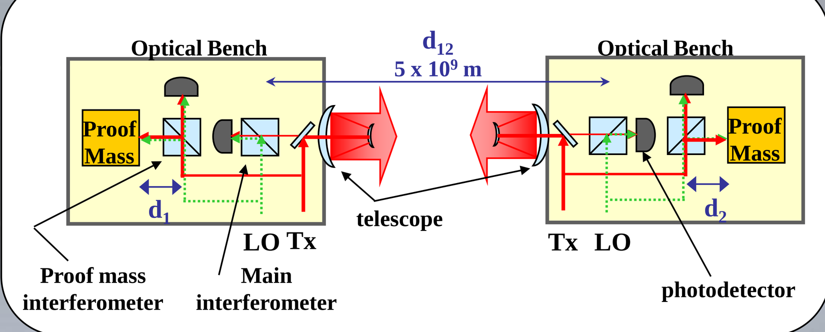
LISA Pathfinder Mission: Technology Demonstrator

- Single spacecraft
- Two proof-masses
- Interferometric metrology between proof-masses
- Orbit around Earth-Sun L1
- Launch in 2009



Interferometric Measurement System (IMS)

- Goal: Measure changes in Proof Mass separation of ~10 picometers over 5 million km arms
- Accomplished by making a series one one-way measurements between spacecraft and combining the results in post-processing



LISA uses a 3-part distance measurement between proof masses on separate spacecraft

Short arm (d_1+d_2) + long arm (d_{12}) = d_{tit}

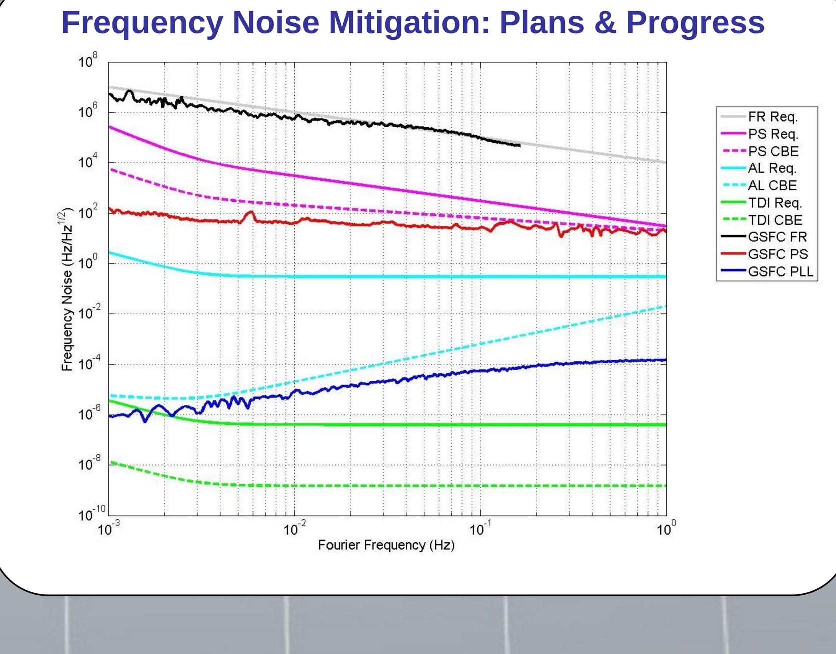
High Level IMS Error Budget

$\times 10^{-12} \frac{m}{\sqrt{Hz}} \sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$

Effect	Total per group	Sub -Allocation	Comments
Total Error Budget	**18.0**		
Contingency (35%)	**6.3**		Held by System Engineering
Total available for allocation	**11.7**		RSS of subsystems
Subsystem Allocations			
Shot noise	7.7		100 pW received power
Pathlength noise	7.0		RSS of sub-allocations
Pointing Errors		5.3	
Telescope pathlength stability		1	
Optical bench pathlength stability		4.5	
Measurement noise	**5.4**		RSS of sub-allocations
Photoreceiver errors		3	
Residual laser frequency noise		2	
Residual clock frequency noise		3	
Phasemeter noise		1	
ADC jitter		1	
Phase reconstruction		1	
straylight		2	

A detailed error budget specifies the requirements on various components of the IMS. The allocations are specified in terms of equivalent path length noise.

Frequency Noise Mitigation: Plans & Progress



The LISA frequency noise mitigation plan combines three techniques to achieve 13+ orders of magnitude noise rejection over the free-running frequency noise. Shown here are requirements (Req.), current best estimates (CBE), and laboratory measurements (GSFC) at four states: free-running (FR), pre-stabilized (PS), arm-locked (AL), and time-delay interferometry (TDI).