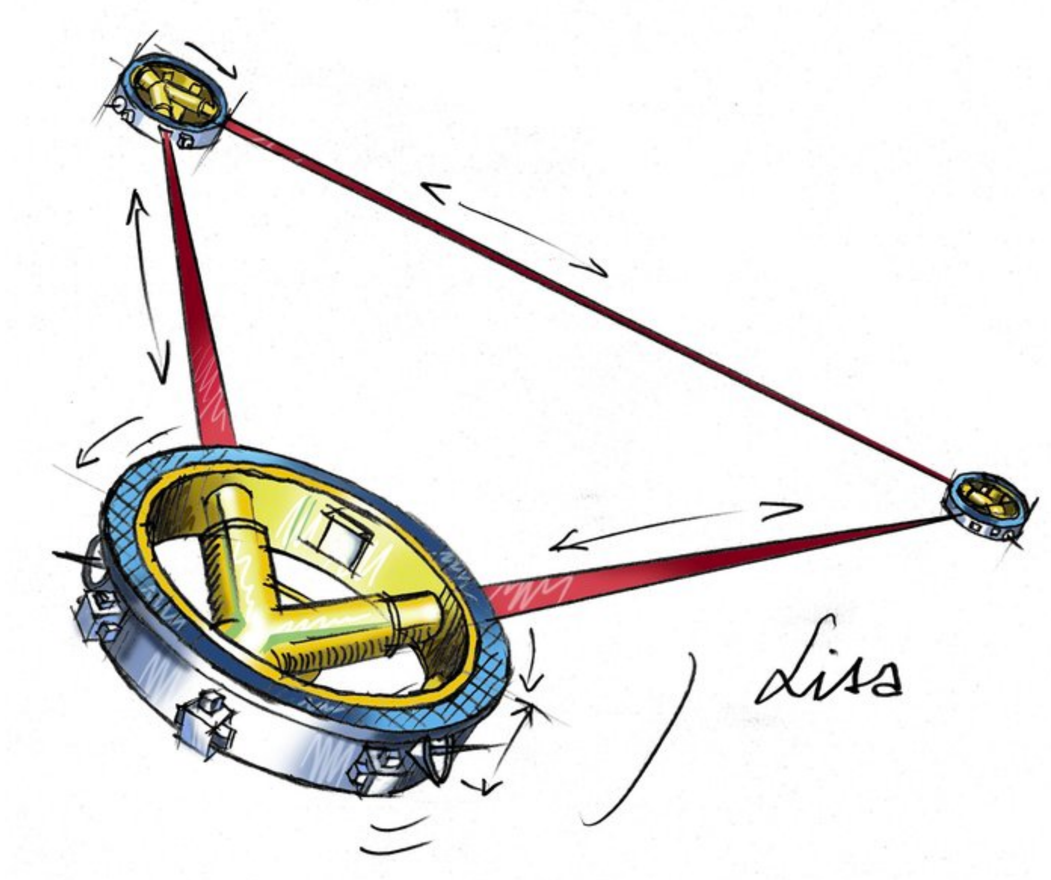
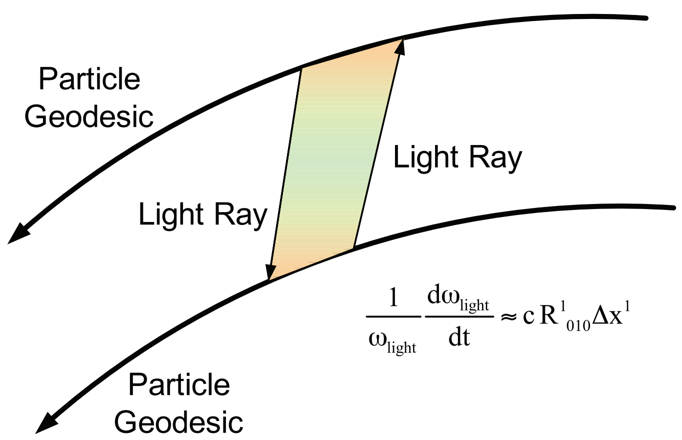
Mission Architecture Overview

Ira Thorpe, NASA/GSFC
On behalf of the L3ST & TAG
2016.03.10



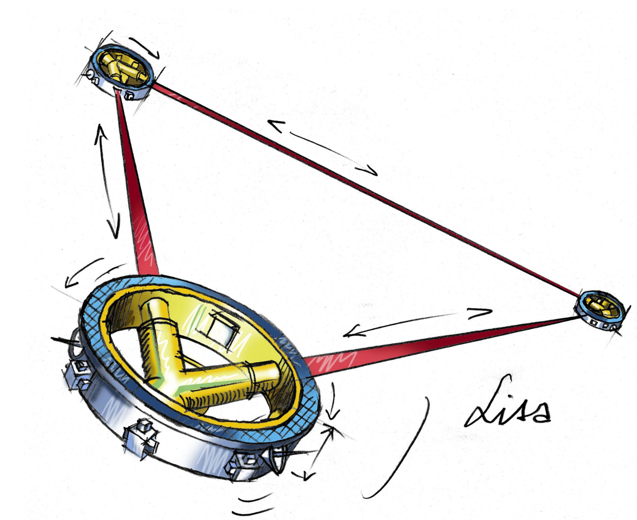
Basic Measurement Concept

Textbook GW detector



Exchange photons between inertial particles to measure variations in curvature caused by GWs.

LISA

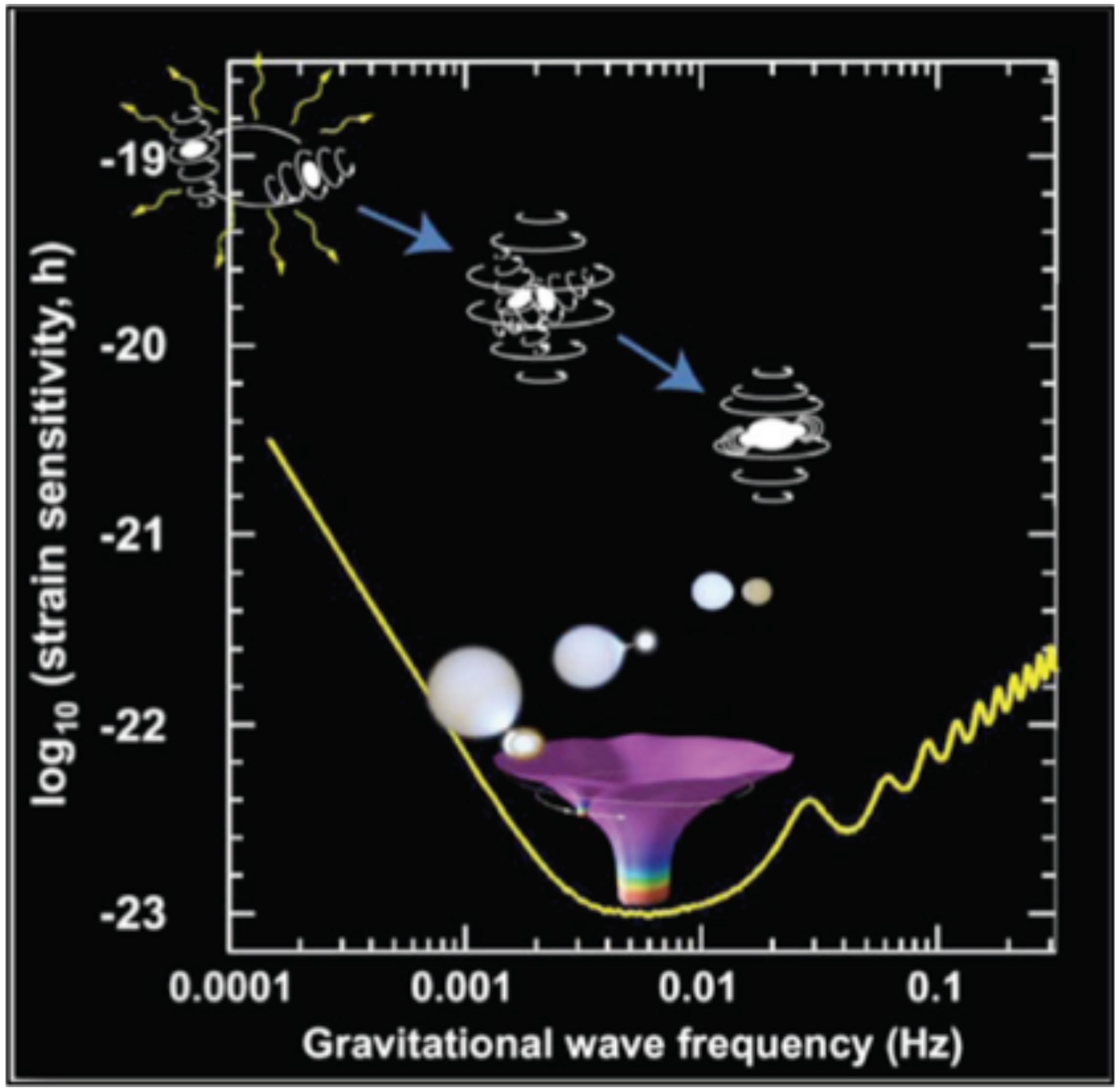


“Inertial particles” → drag-free test masses

“photon exchange” → heterodyne interferometry

Sensitivity Curve

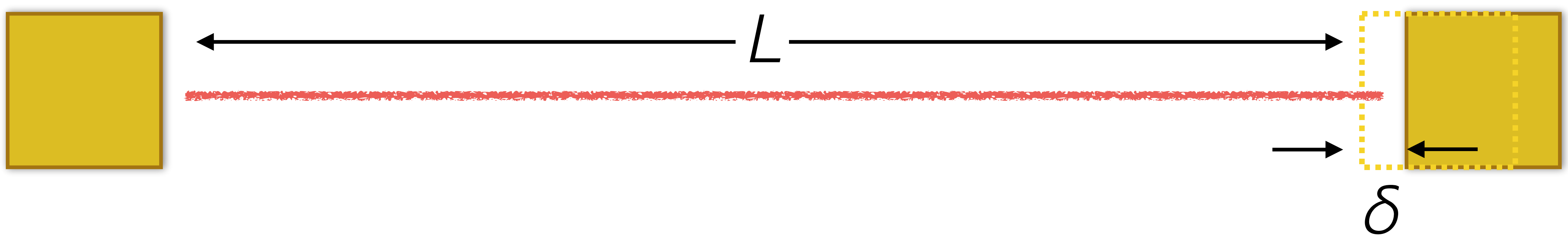
- “Rosetta Stone” between instrument performance and science performance
- Other important factors
  - number of arms
  - orbital modulation
  - mission lifetime



Building a Sensitivity Curve

Arm response · measurement noise · acceleration noise

$$\tilde{\delta}(f) = L\tilde{h}(f)\sin(2\pi f c/L)\exp(-2\pi i f c/L) + \tilde{n}_x(f) + (2\pi f)^{-1}\tilde{n}_a(f)$$

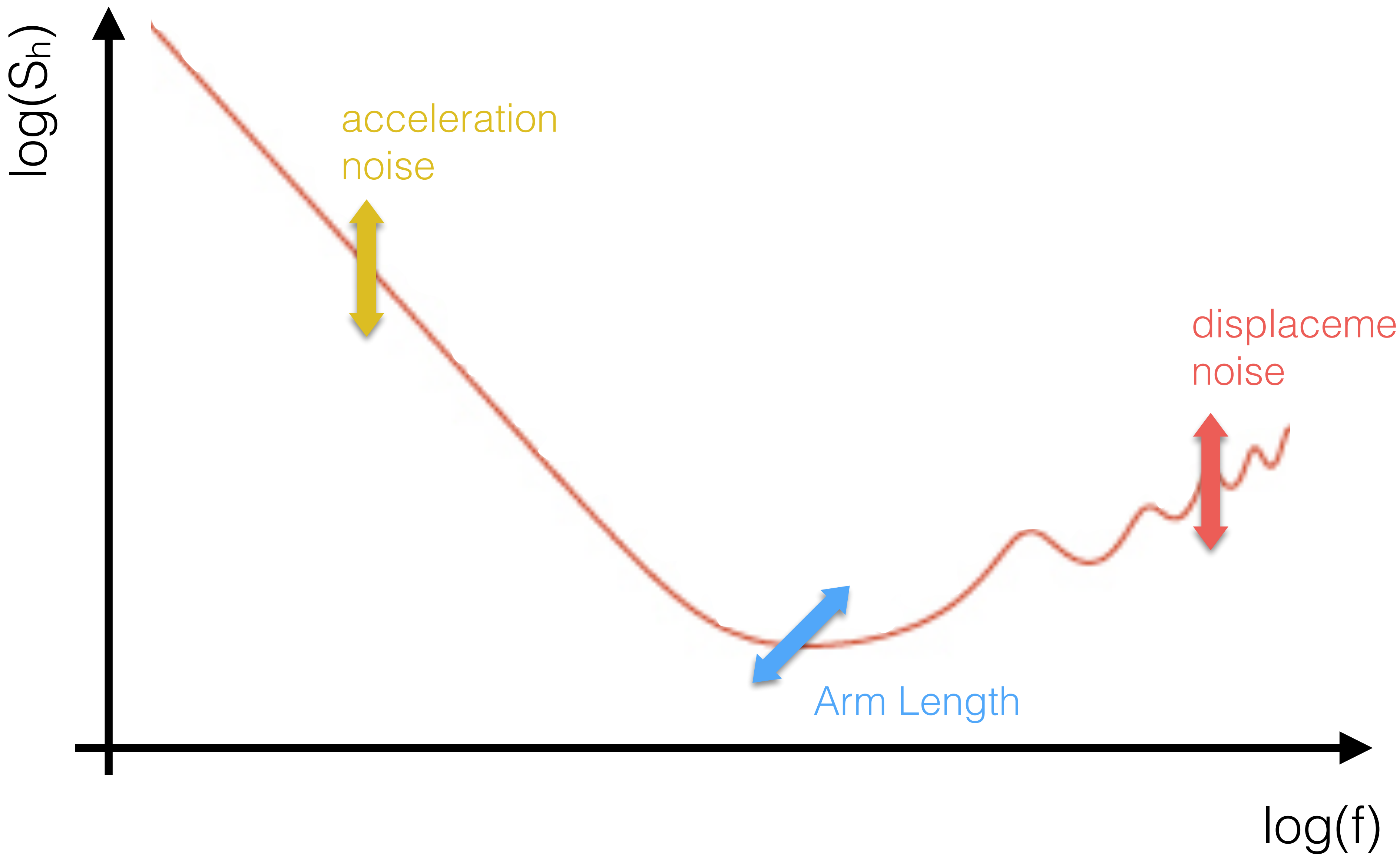


Equivalent Strain Noise

$$S_h = \left|\frac{\partial\tilde{\delta}}{\partial\tilde{h}}\right|^{-2}\left(\left|\frac{\partial\tilde{\delta}}{\partial\tilde{n}_x}\right|^{2} S_x + \left|\frac{\partial\tilde{\delta}}{\partial\tilde{n}_a}\right|^{2} S_a\right)$$

Arm response · measurement noise · acceleration noise

Basic Scaling Laws



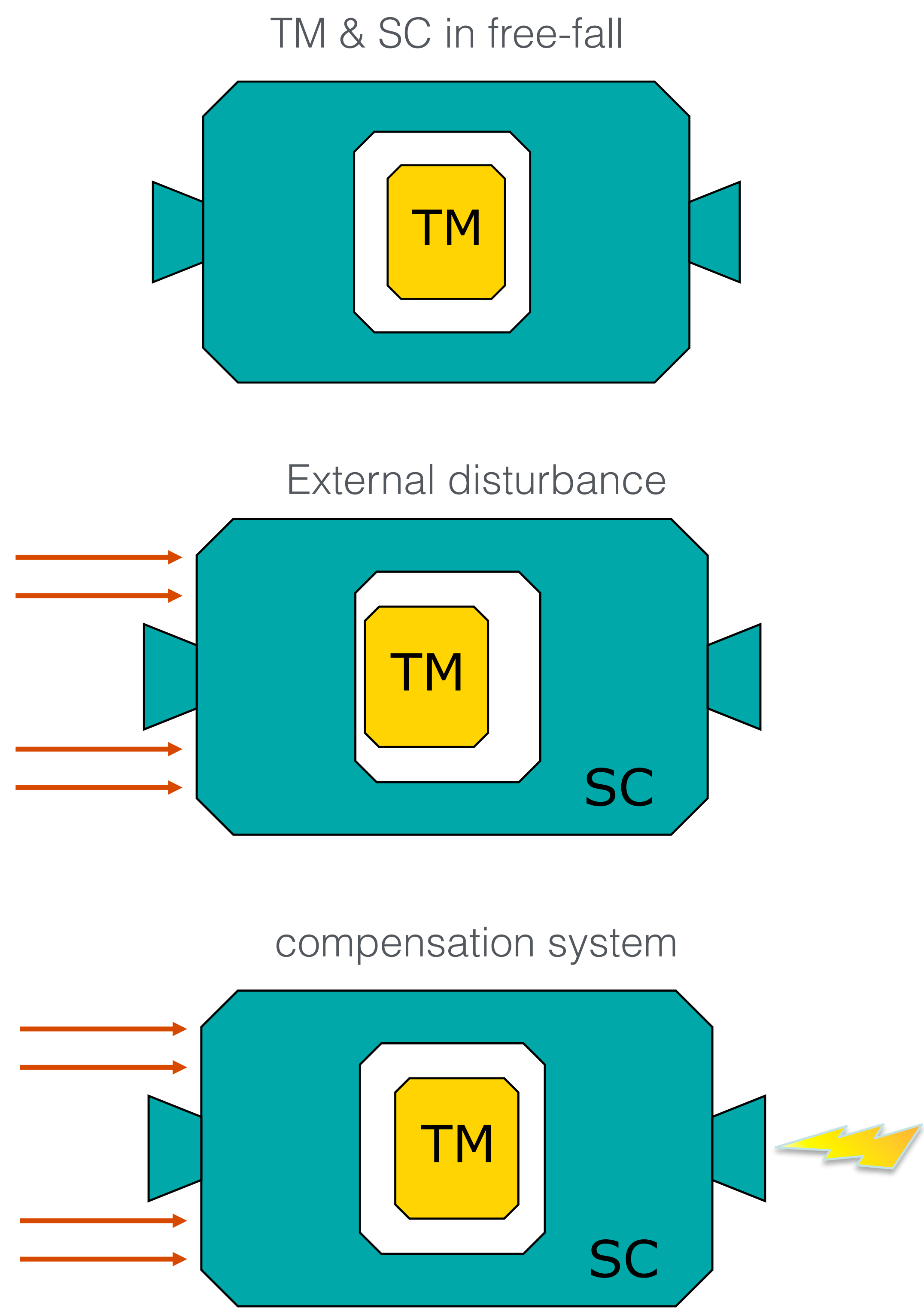
Mitigating Acceleration noise

Drag-free control systems

Drag-free Control

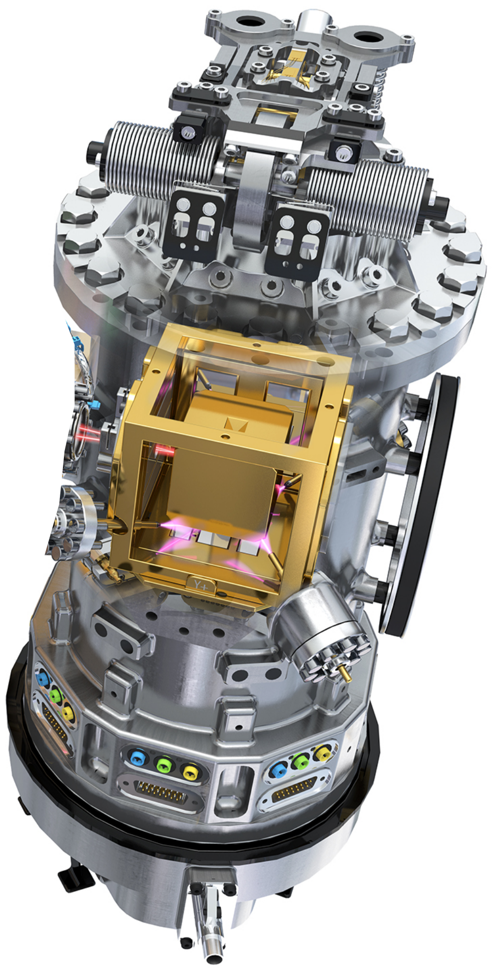
- Summary
  - test mass in free-fall inside spacecraft
  - control system maintains relative position and attitude
- Major Components
  - Test Mass / sensor system
  - control laws
  - actuators (thrusters)

LISA Requirement: $\delta\tilde{a} \sim 3\,\mathrm{fm/s^2/\sqrt{Hz}}$



Gravitational Reference Sensor

- Subsystems
  - 6-axis position/attitude sensing
  - 6-axis electrostatic forcing
  - non-contact charge control w/ UV light
  - launch lock & release mechanisms
- Provide Quiet environment
  - 'low' pressure (~1e-6 Pa)
  - thermal
  - magnetic
  - electrostatic
  - gravitational
- Status
  - Major development item for LPF
  - Recent activities in the US on UV charge control and torsion pendulums (Conklin)

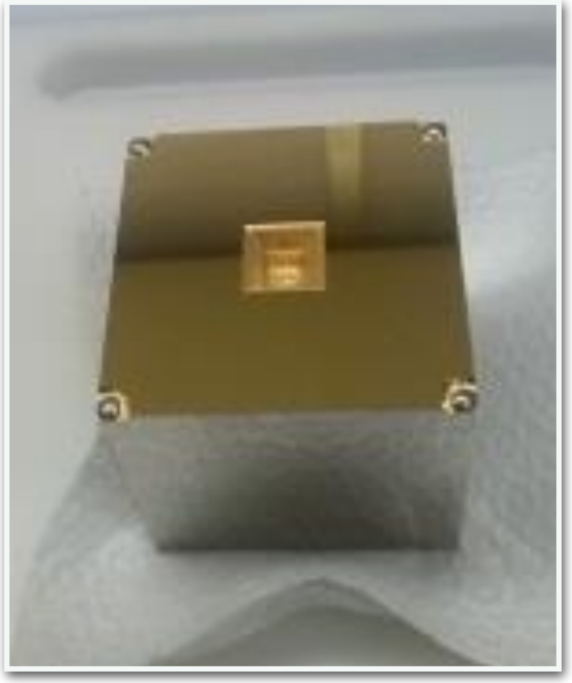


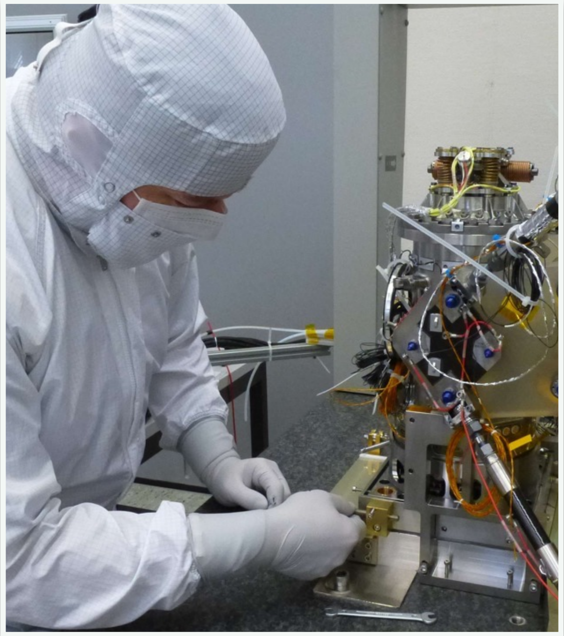
LISA Pathfinder GRS

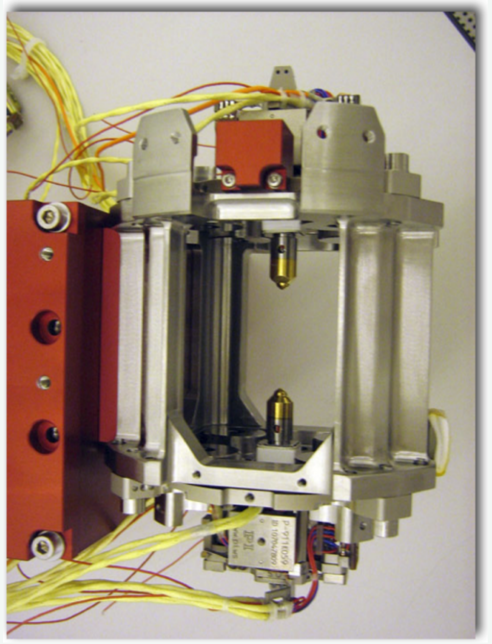
GRS on LPF

lisa pathfinder

- Test mass: 46mm cube of Au-Pt alloy (2 kg)
- electrode housing with 3-4mm gaps
- electrodes used to sense position/attitude and apply forces/torques
- Non-contact charge control via UV lamps
- Housed in titanium vacuum vessel
- Caged during launch, released to electrostatic suspension on orbit

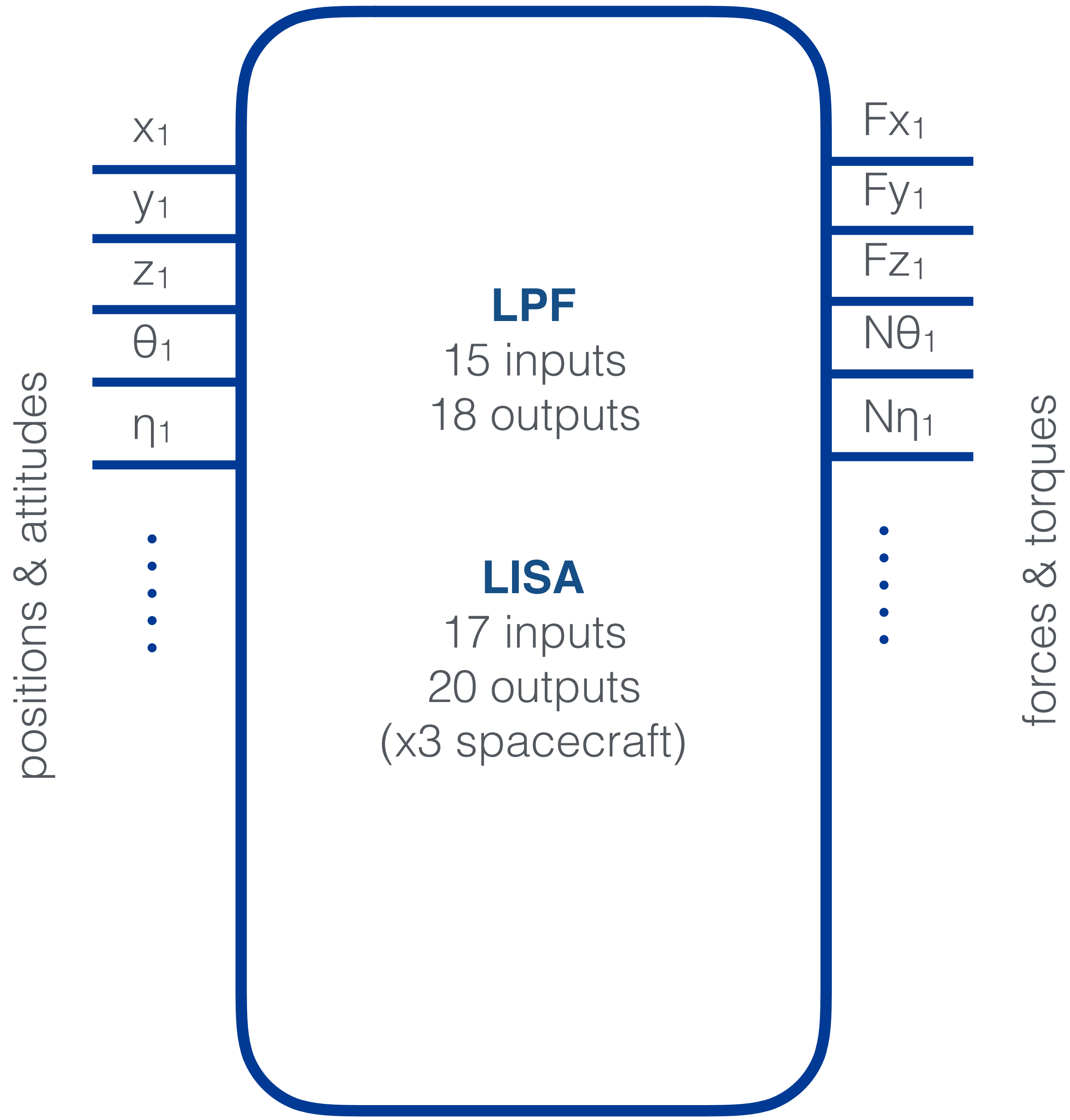






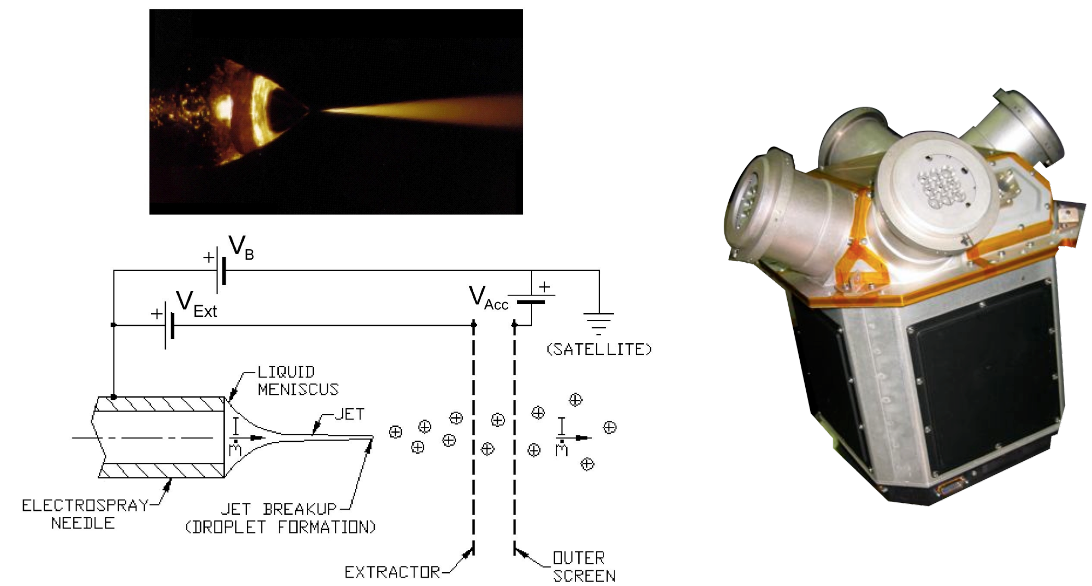
Control System

- Objectives
  - free-fall of test mass(es)
    - along sensitive axis
    - within measurement band
  - constraints
    - test mass angles
    - test mass positions
    - spacecraft attitude
    - spacecraft orbit
- Status
  - Two systems developed for LPF
    - DFACS system (ESA)
    - DCS system (NASA)
  - LISA project supported some design work

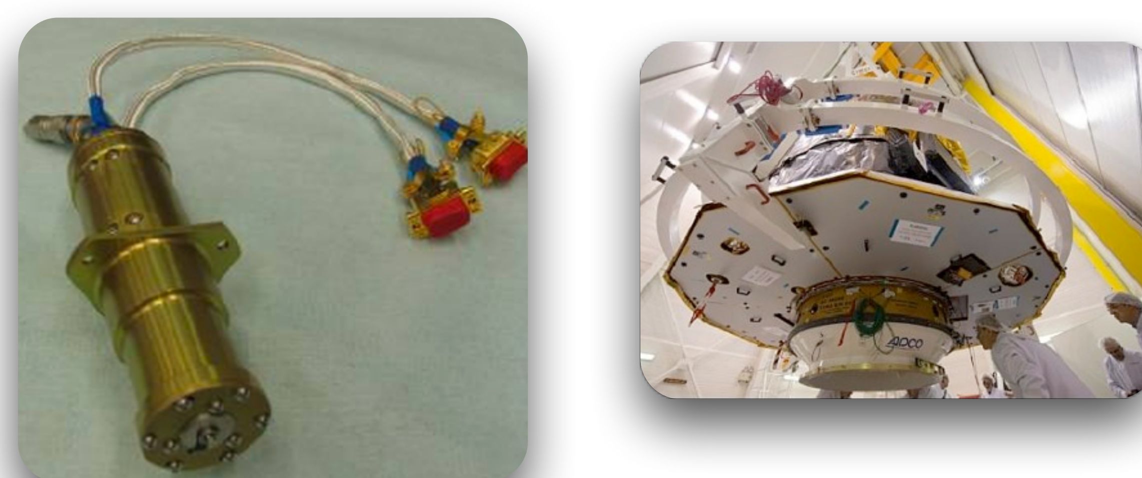


Microthrusters

- Provide position and attitude control of the spacecraft
- Range: 1~100 uN
- Noise: ~ 100nN/Hz$^{1/2}$
- Status
    - Two systems on LPF
        - Cold gas (ESA)
        - Colloidal (NASA)
    - Other potential candidates
        - FEEPs
        - RITs
        - …



Colloidal MicroNewton Thruster (JPL/BUSEK)



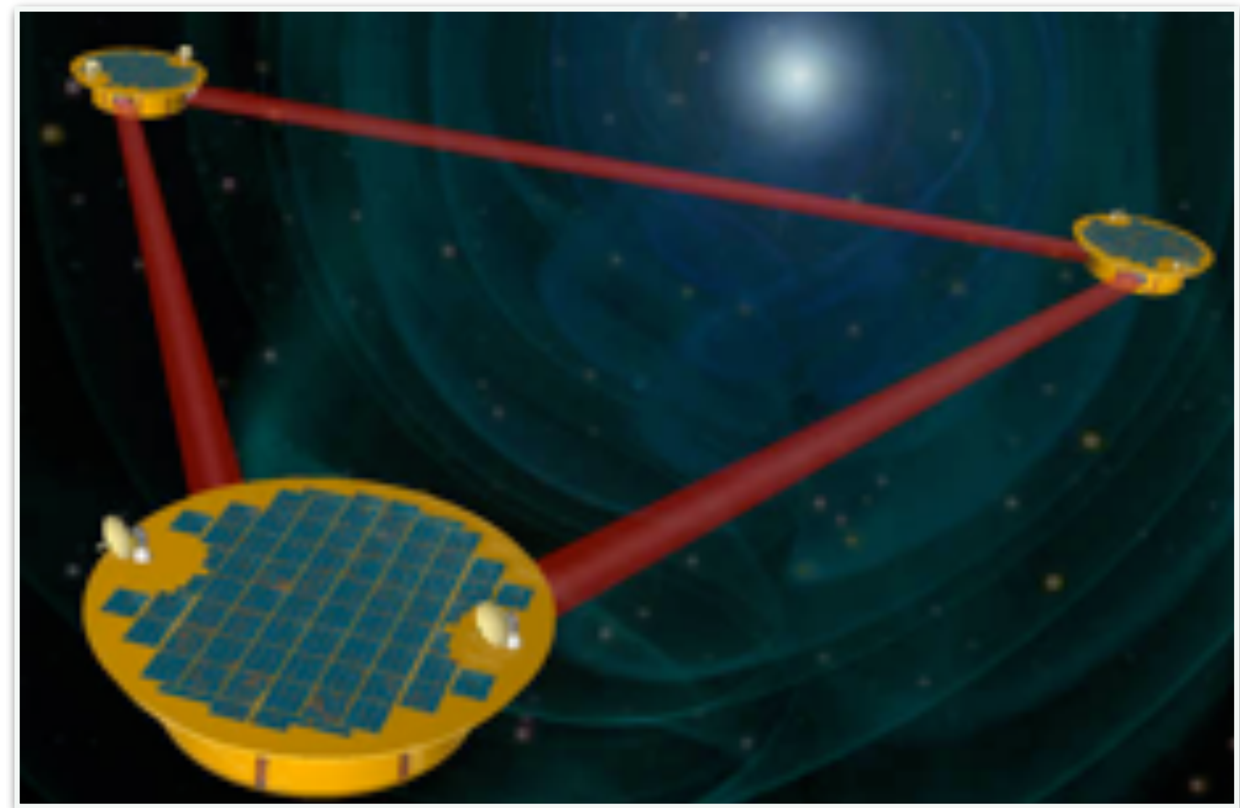
Cold Gas Microthruster (photos from GAIA)

Displacement Measurement

Long-baseline heterodyne interferometry

Overall Design

- Build constellation from one-way 'links' (4 or 6)
  - 'back links' made at each vertex using an optical fiber.
- each link measurement contains large noise + small signal
- combine link measurements on ground to extract signal (TDI). Accounts for varying arm-lengths.
- Fundamental limit is shot noise
- Many other 'technical' noises. Error budget designed so that shot noise dominates.
- Many options to meet overall system requirement (e.g. trade laser power, telescope diameter, etc.)

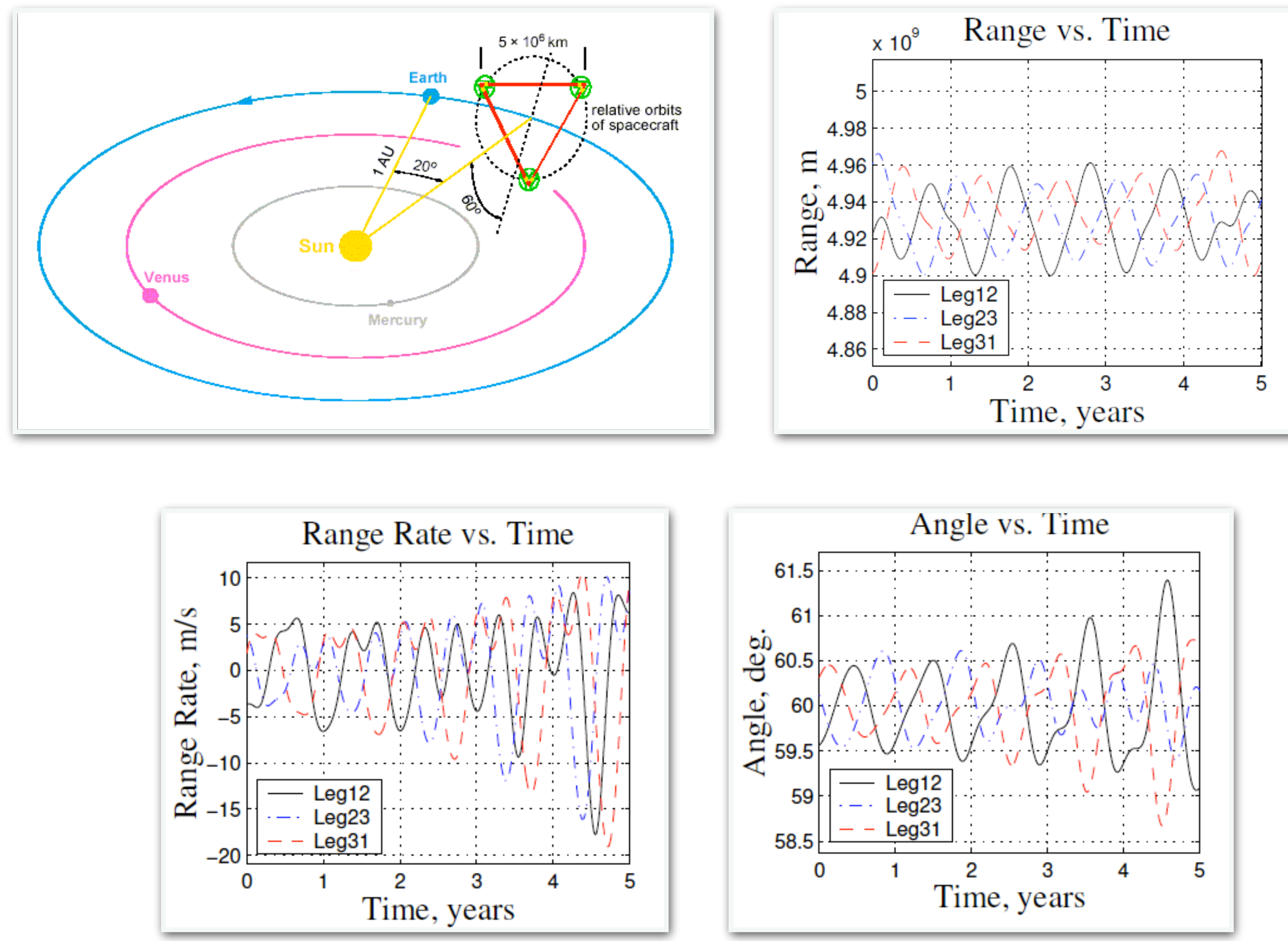


LISA Requirement for L = 5 Gm:

$$\delta\tilde{x} = 18\,\mathrm{pm}/\sqrt{\mathrm{Hz}}\left[1 + (f/3\,\mathrm{mHz})^{-4}\right]^{1/2}$$

Orbit Design & Consequences

- Spacecraft are each on independent orbits
- No ‘formation-flying’
- No or minimal station-keeping
- Constellation geometry is time-varying
  - annual effects drive instrument requirements
    - phase meter frequency range
    - laser stability
    - pointing requirements
    - telescope field-of-view
  - secular effects limit lifetime

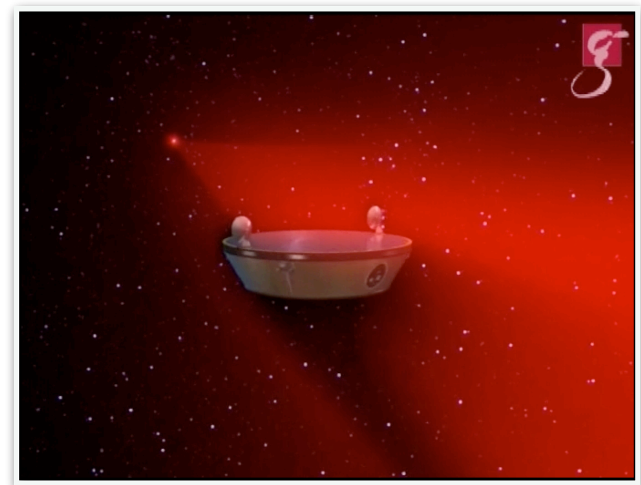


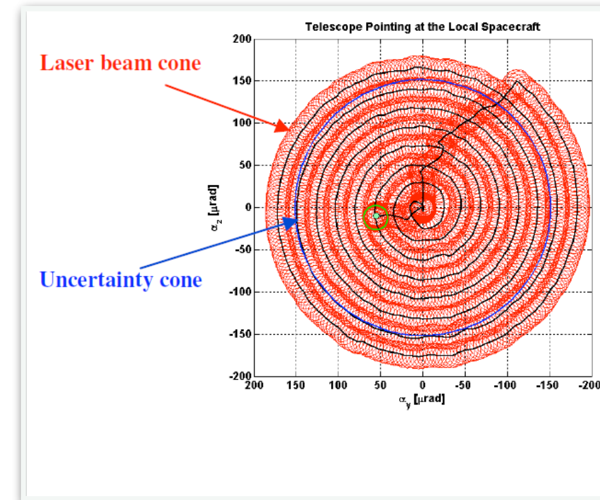
Orbit Models for Classic LISA

Constellation Pointing

Initial Acquisition for LISA

- Information: orbital ephemeris, star trackers
- Active search & alignment: positional scan, CCD acquisition, quadrant photoreceivers, wavefront sensing

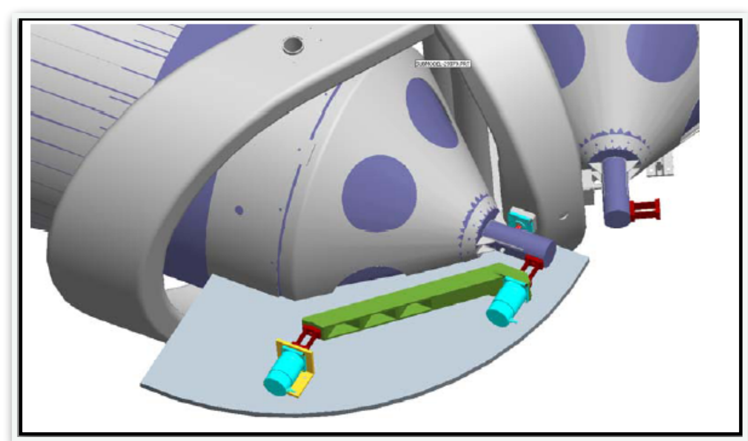




Pointing Maintenance for LISA

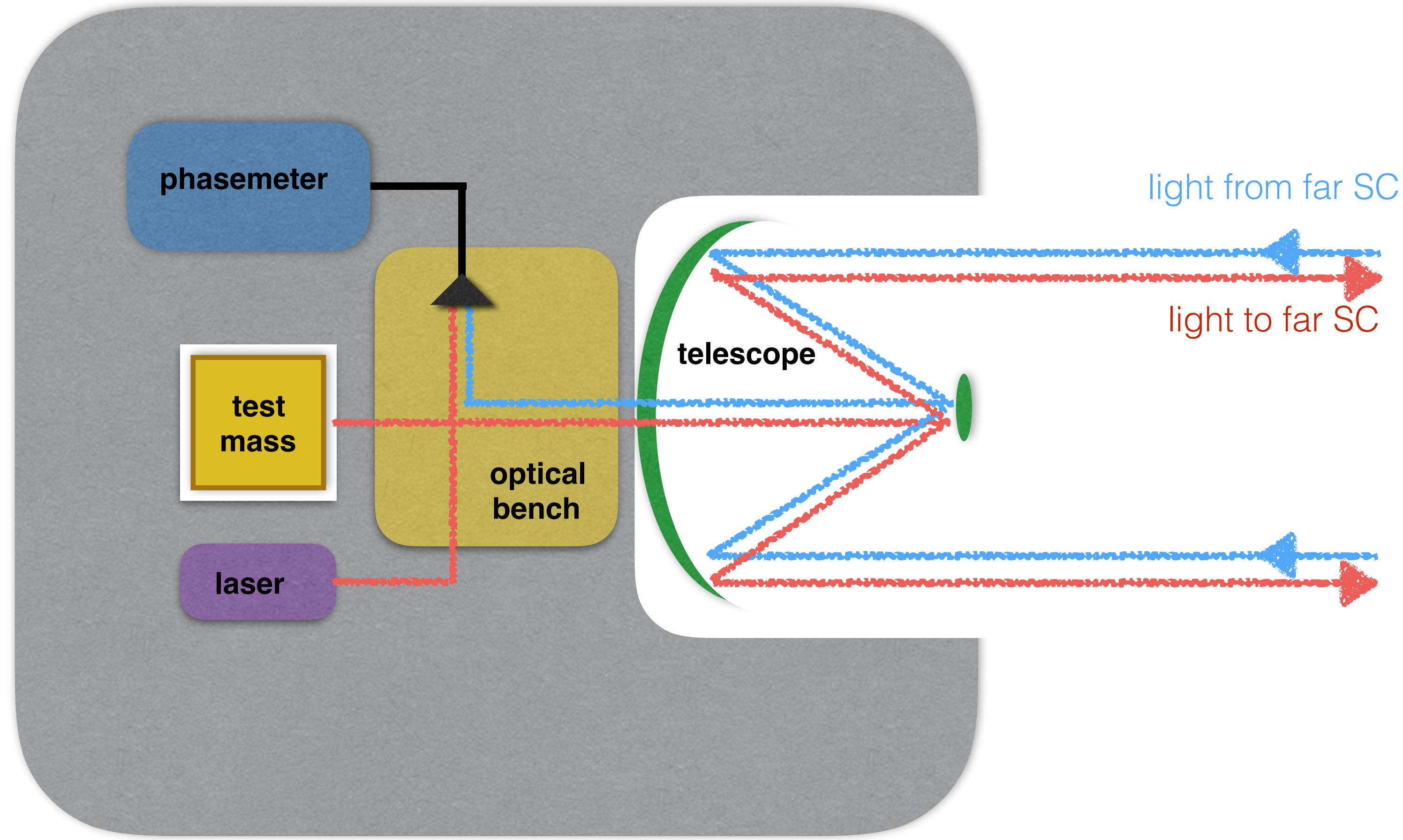
- Relative beam angles measured locally using differential wavefront sensing
- Optical Assembly Articulation Mechanism (OATM): Accounts for variation in interior angles of constellation: 1° dynamic range
- Point-ahead actuator (PAA): removes angle between transmitted and received beam due to relative transverse SC motion: ~3μrad
- "In-field guiding" Option: replace OATM with wide-FOV telescope and small steering mirror. Possibly eliminate back-link fiber between optical benches

← Major system trade



Single Optical Payload

- each link measurement contains large noise + small signal
- combine link measurements on ground to extract signal (TDI)
- Fundamental limit is shot noise
- Many other 'technical' noises, designed to be hidden underneath shot noise.
  - laser frequency noise
  - optical path length noise
  - geometric cross-talk
  - etc.



Laser
provide stable light source

Telescope
mitigate diffraction losses

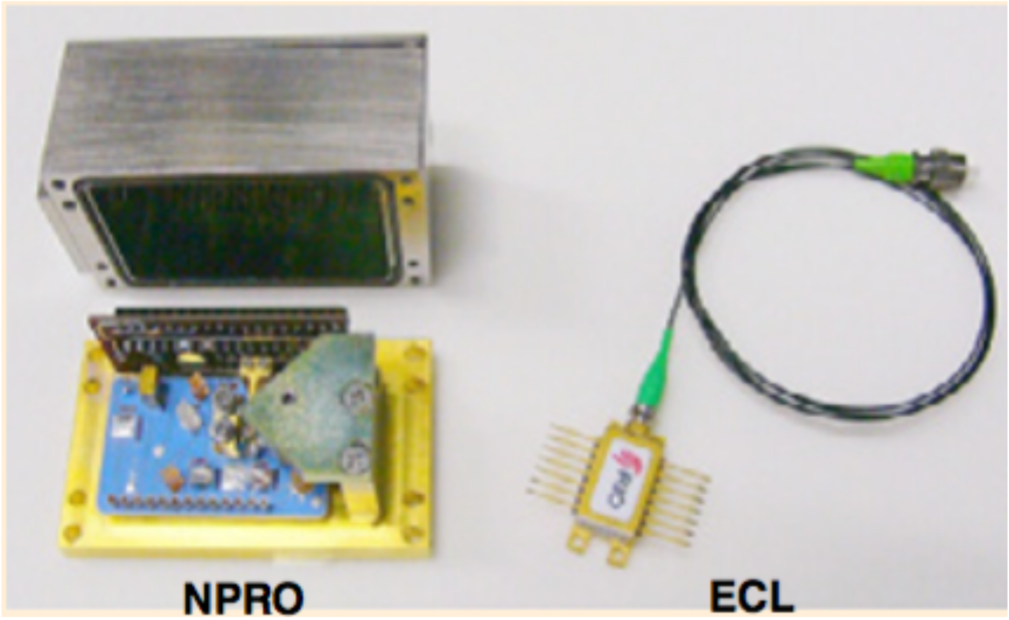
Phase meter
track and measure
time-dependence of interference
frequency and phase stabilization
optical measurement system control

Optical Bench
generate interference patterns

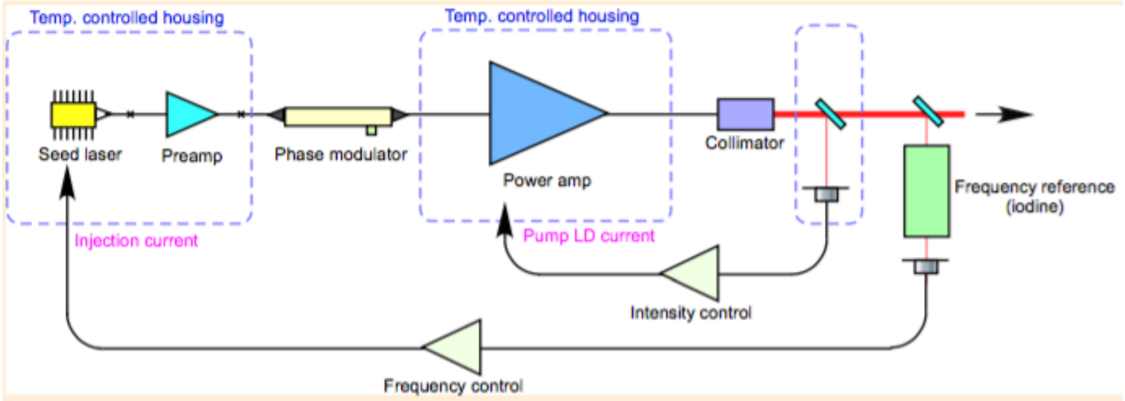
Laser subsystem

- Key requirements
  - high power (1~2 W)
  - frequency stable
  - intensity stable
  - modulated for clock transfer
- Subsystems
  - 'seed' or 'master' oscillator
  - phase modulator
  - power amplifier
- Status
  - No complete system developed
  - LPF laser suitable for seed oscillator
  - NASA effort to develop system around fiber laser (Camp)

Seed laser options



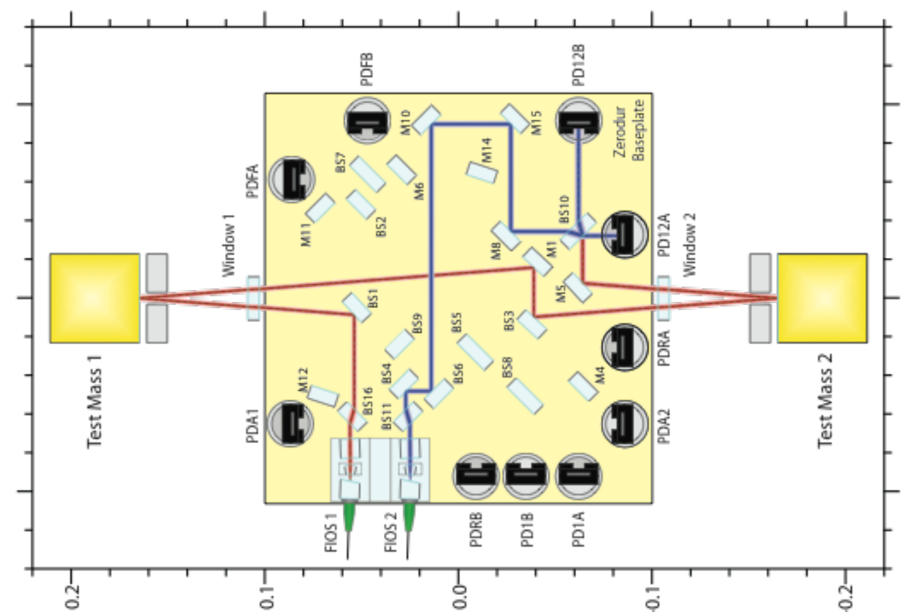
Example laser system



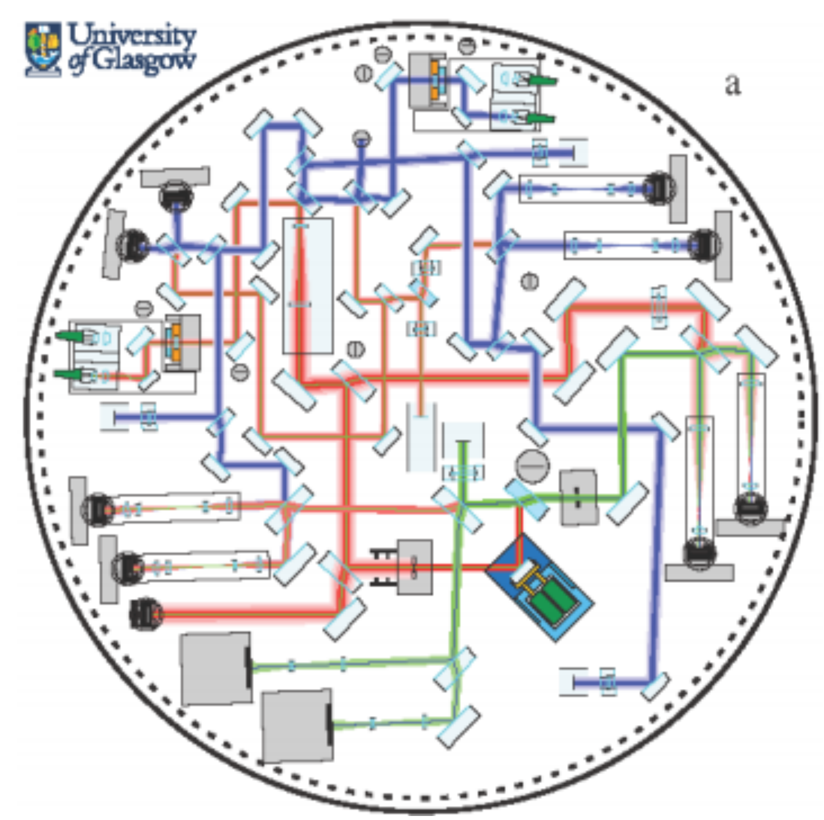
Optical Bench Subsystem

- Key requirements
  - Dimensional Stability
  - low scattered light
  - accurate construction
- Subsystems
  - fiber injectors
  - pointing mechanisms
  - back link fiber
- Status
  - Materials and construction techniques developed for LPF. Major technology development item.
  - LISA design studies underway in Europe
  - Some efforts underway in the US (Mueller)

LPF (1 of 1)

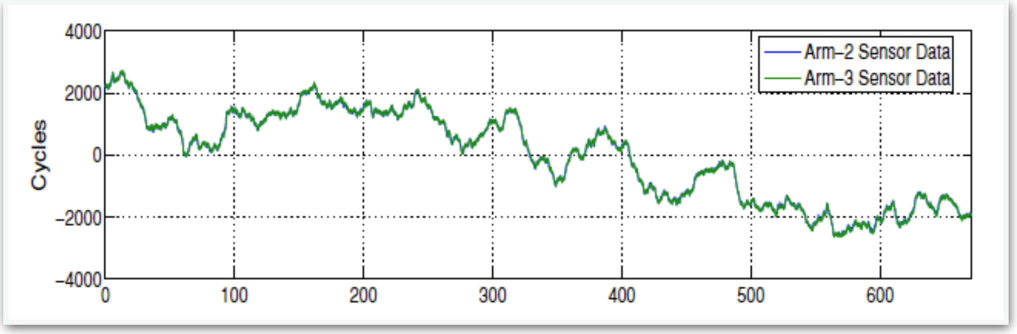


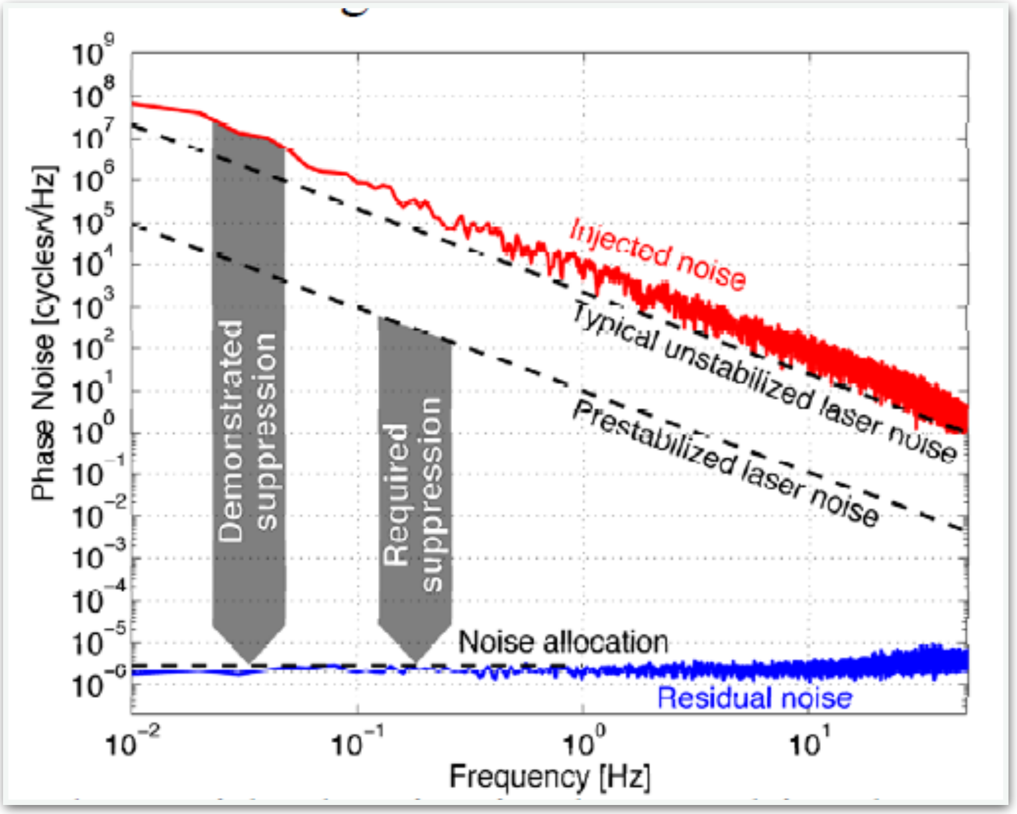
LISA (1 of 6)



Phase measurement subsystem

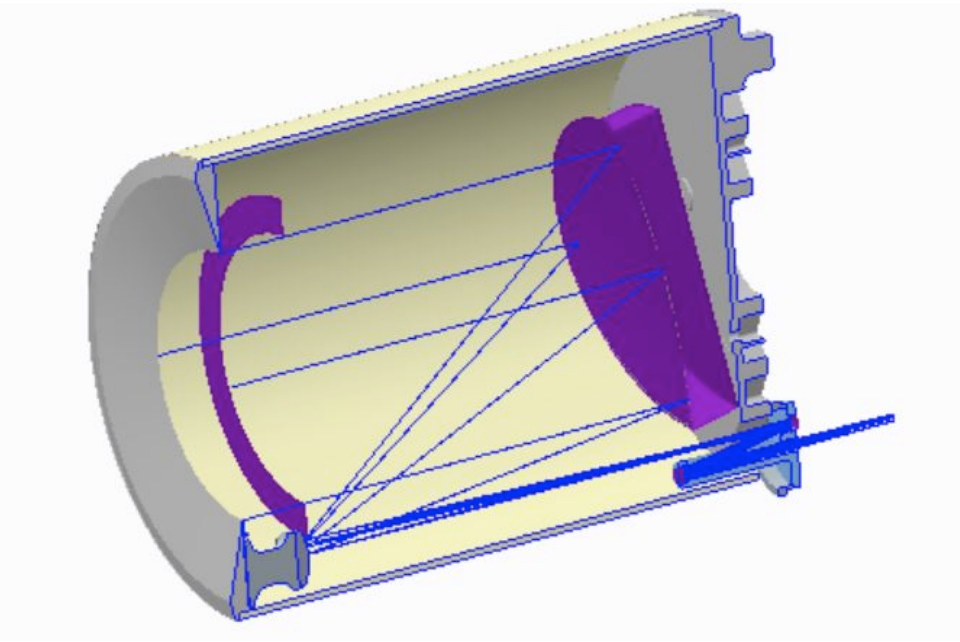
- Key requirements
  - Large dynamic range (μcycle/Hz$^{1/2}$ noise in MHz/Hz$^{1/2}$ noise)
  - high linearity
  - large channel count
- Subsystems
  - photorecievers & analog front-end
  - digital signal processing
  - instrument control (e.g. phase locking, frequency stabilization, etc.)
- Status
  - Major US development efforts during LISA project (Klipstein)
  - Parallel efforts in Europe
  - Laser Ranging Processor for GRACE-FO has similar requirements. Launch 2017?



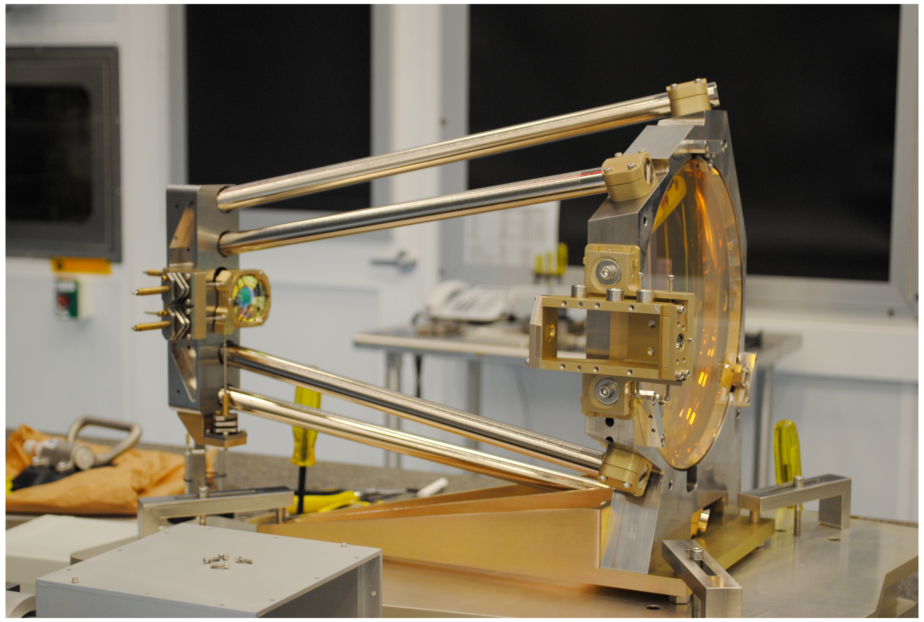


Telescope

- Key requirements
  - Optical path length stability
    - thermal / materials
  - Scattered light mitigation
  - wavefront quality
  - manufacturability (~6 units + spares)
- Subsystems
  - core optics
  - focusing/steering mechanism(s)
  - digital signal processing
  - instrument control (e.g. phase locking, frequency stabilization, etc.)
- Status
  - Some efforts during LISA project (Astrium, GSFC, U Florida)
  - Recent efforts at NASA (Livas)



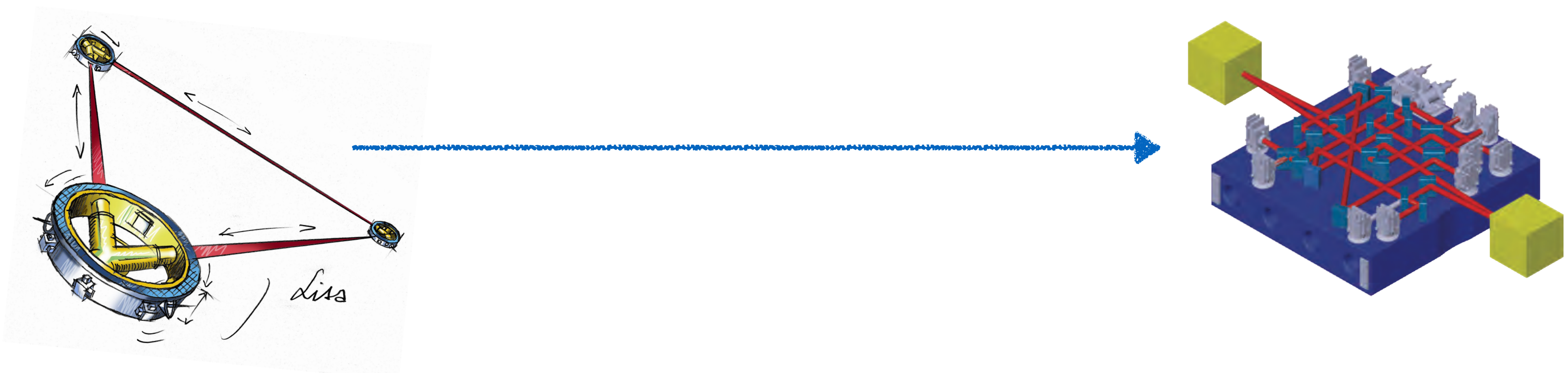
Design and Prototype at GSFC (Livas)



Related Mission Activities

LISA Pathfinder and GRACE-FO

LPF Measurement Concept

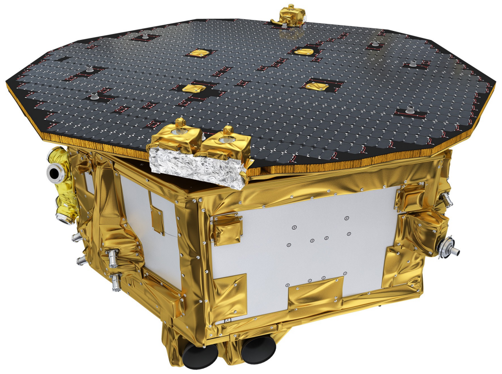


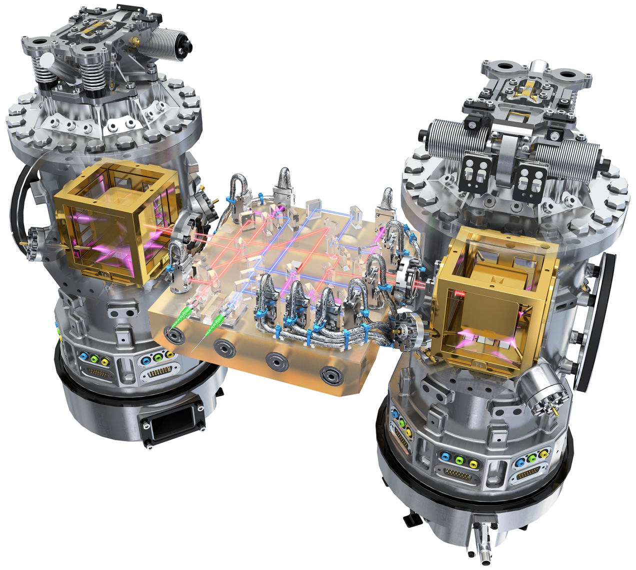
Shrink one LISA arm onto a single spacecraft

- Lose all of the signal
- Keep most of the noise

Key Components

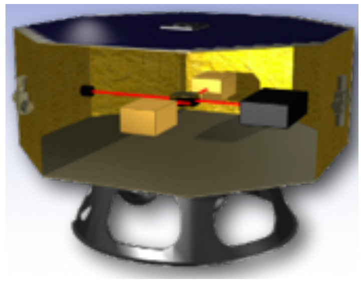
- Spacecraft (ESA)
  - Micronewton thrusters (cold gas)
  - Drag-free control laws
  - Emphasis on mechanical, thermal, & gravitational stability
- LISA Technology Package (ESA & European Consortium)
  - Two gravitational reference sensors
  - Optical Metrology System
  - Thermal/Magnetic Diagnostic System
- ST7-DRS (NASA/JPL)
  - Micronewton thrusters (colloidal)
  - Drag-free control laws (use LTP sensors/actuators)



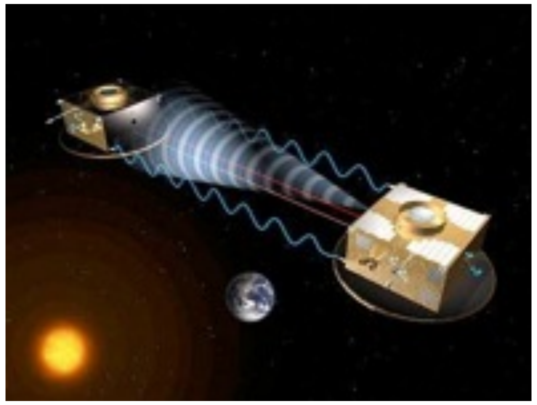


History of LPF

- 1998: **ELITE** (**E**uropean **LI**sa **TE**chnology) proposed
  - Homodyne interferometer
  - Launch date 2002

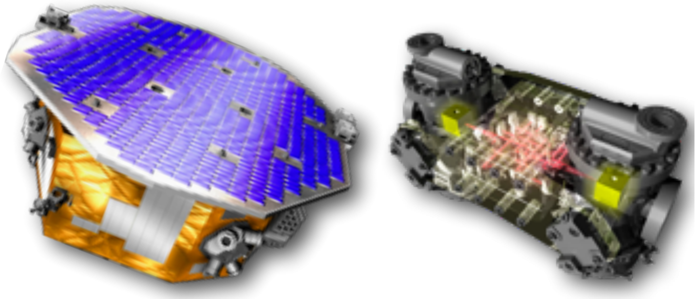


- 2000: ELITE proposed as **SMART-2** (**S**mall **M**issions for **A**dvanced **R**esearch in **T**echnology)
  - Two spacecraft, three payloads
  - LISA Pathfinder (ESA), Darwin Pathfinder (ESA), Disturbance Reduction System (NASA)



- 2001: **SMART-2** Descoped and re-named **LISA Pathfinder**
  - Darwin Pathfinder cancelled
  - single spacecraft, two payloads
  - LISA Technology Package (Europe) and DRS (NASA)

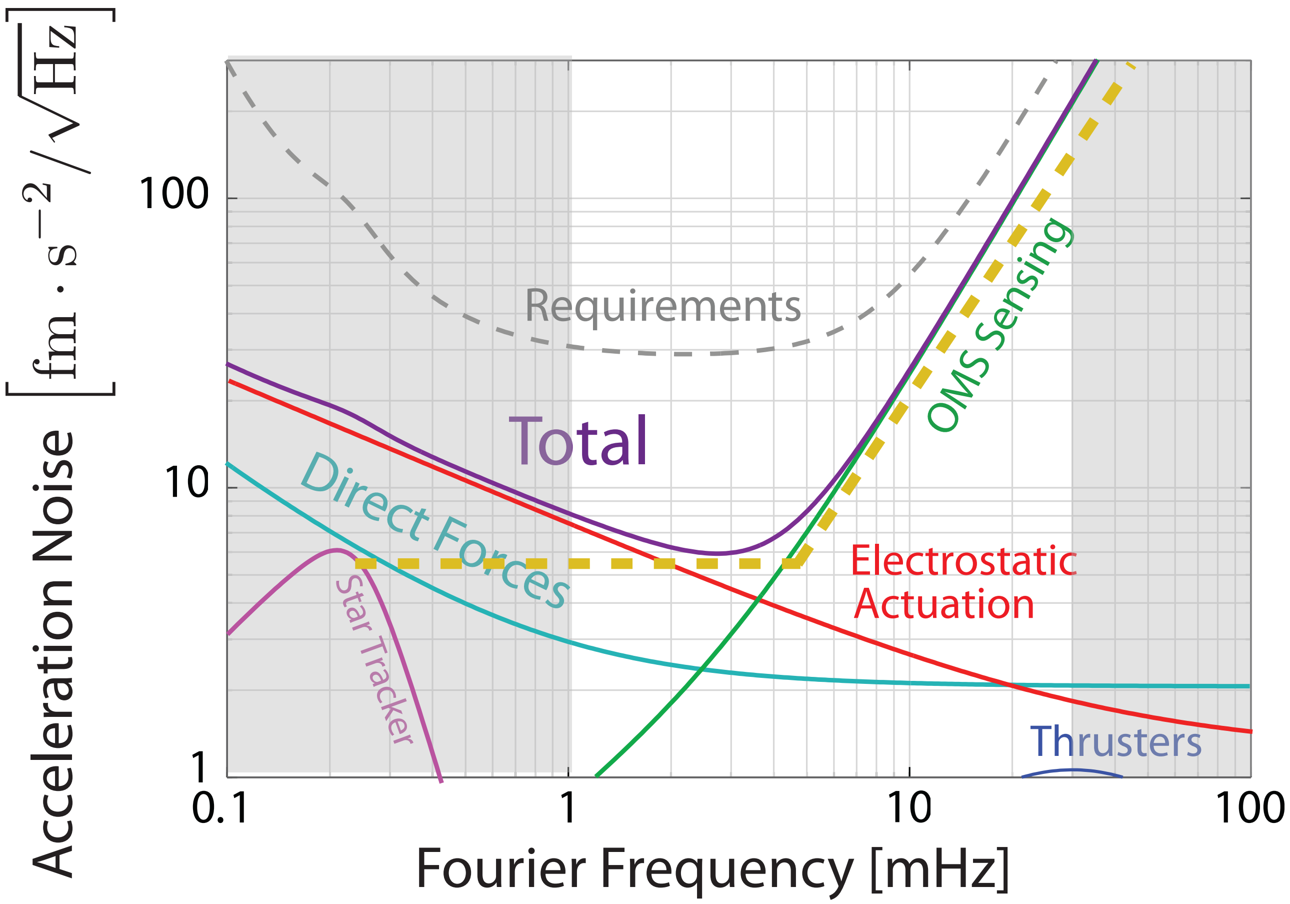
- 2005: DRS Descoped
  - DRS interferometer and inertial sensor removed
  - DRS control laws and thrusters will use LTP sensors



What we learn from LPF

- First demonstration of high-precision drag-free system
- ~1000x lower disturbance environment than previous missions (e.g. GRACE)
- Measure noise couplings (thermal, magnetic, etc.)
- Gain experience with operating system
- Components relevant to LISA*
  - GRS
  - thrusters
  - optical bench construction
  - laser

* Some tweaks needed in all cases, in some cases major changes are needed



LPF pre-flight best estimate

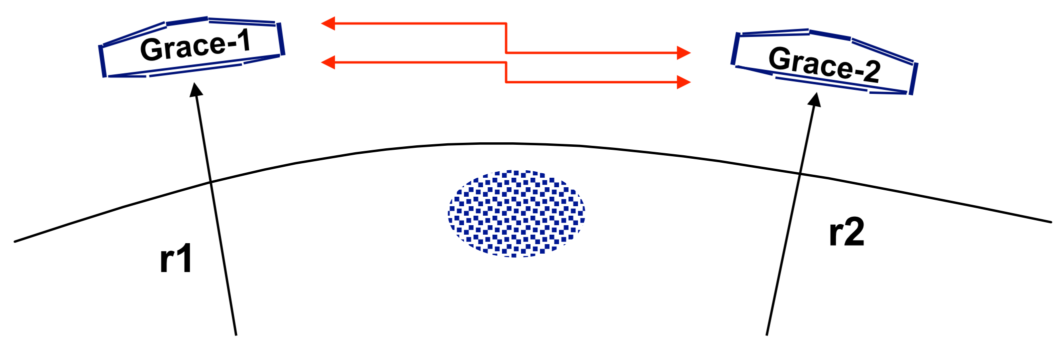
approximate LISA requirement

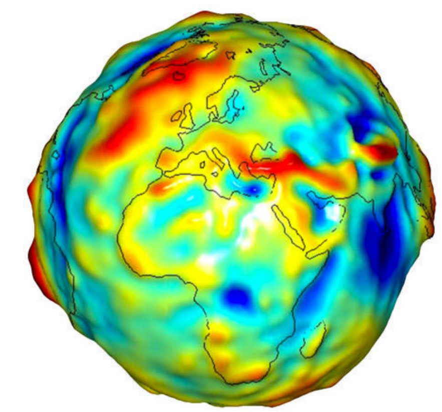
Actuation noise (suppressed in drift mode)

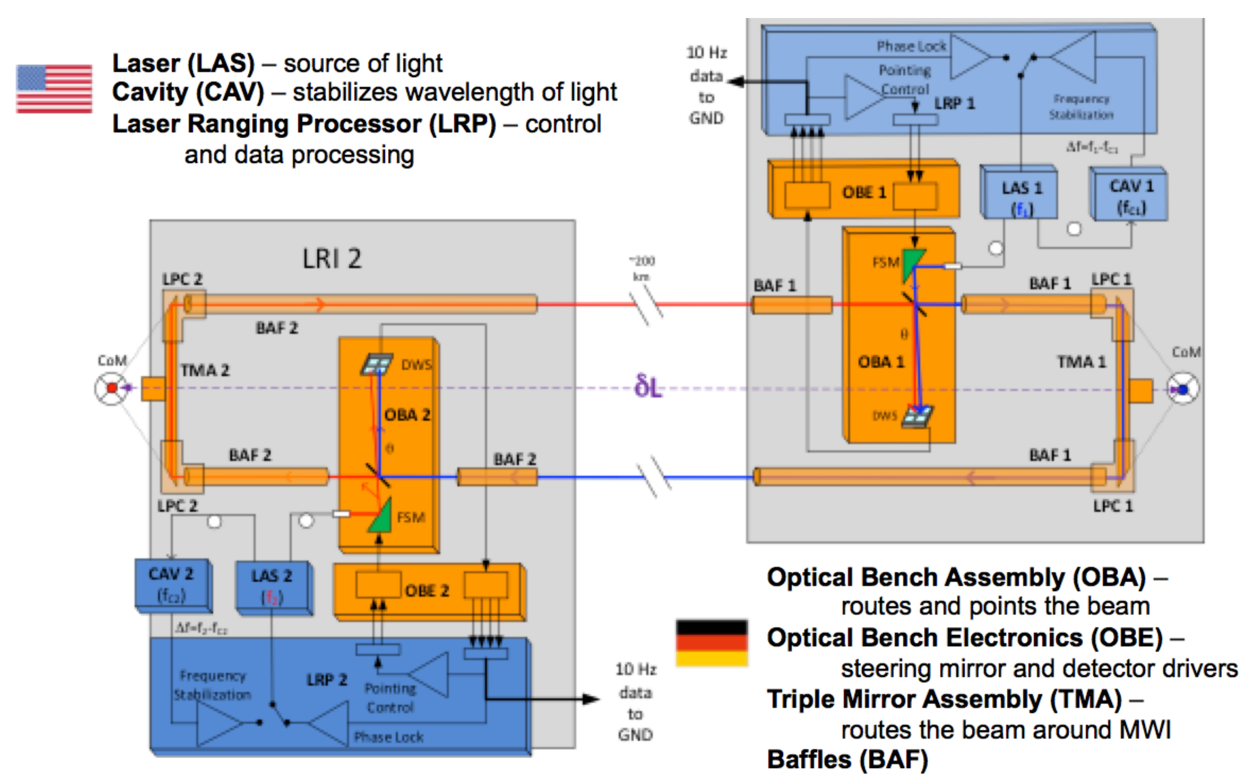
test mass forces (inform LISA design)

GRACE-FO

- **Data Continuity for GRACE**
  - map gravity anomalies by tracking distance between a pair of satellites in LEO
  - accelerometer to correct for atmospheric drag
  - microwave ranging as primary science instrument
  - **laser ranging as tech. demo.**
- **Laser Ranging Instrument (LRI)**
  - First demonstration of inter spacecraft laser interferometry
  - LISA “heritage”

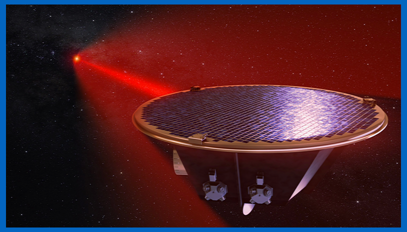






What we learn from GRACE-FO

- most LISA-like interferometry configuration likely to fly before LISA
- reduce risk for key LISA components (e.g. phase meter, cavity)
- reduce risk for key LISA operations (e.g. link acquisition)
- LRI *could* be used to demonstrate specialized LISA measurement techniques such as TDI and arm-locking (McKenzie)

Parameter	LISA 	GRACE-FO 
Arm Length	~ 5 x 10^6 km	~ 270 km
Round-trip time	~ 33 s	~ 1.8 ms
Tx Laser Power	~ 2W	~ 25mW
Aperature	~30 cm	~1 cm
Rx Laser Power	~ 100 pW	~ 100 pW
Doppler Amplitude	~20 MHz	~ 18 MHz
Doppler Period	1 year	~90 min
Launch Date	~2034	2017

Considerations for L3ST

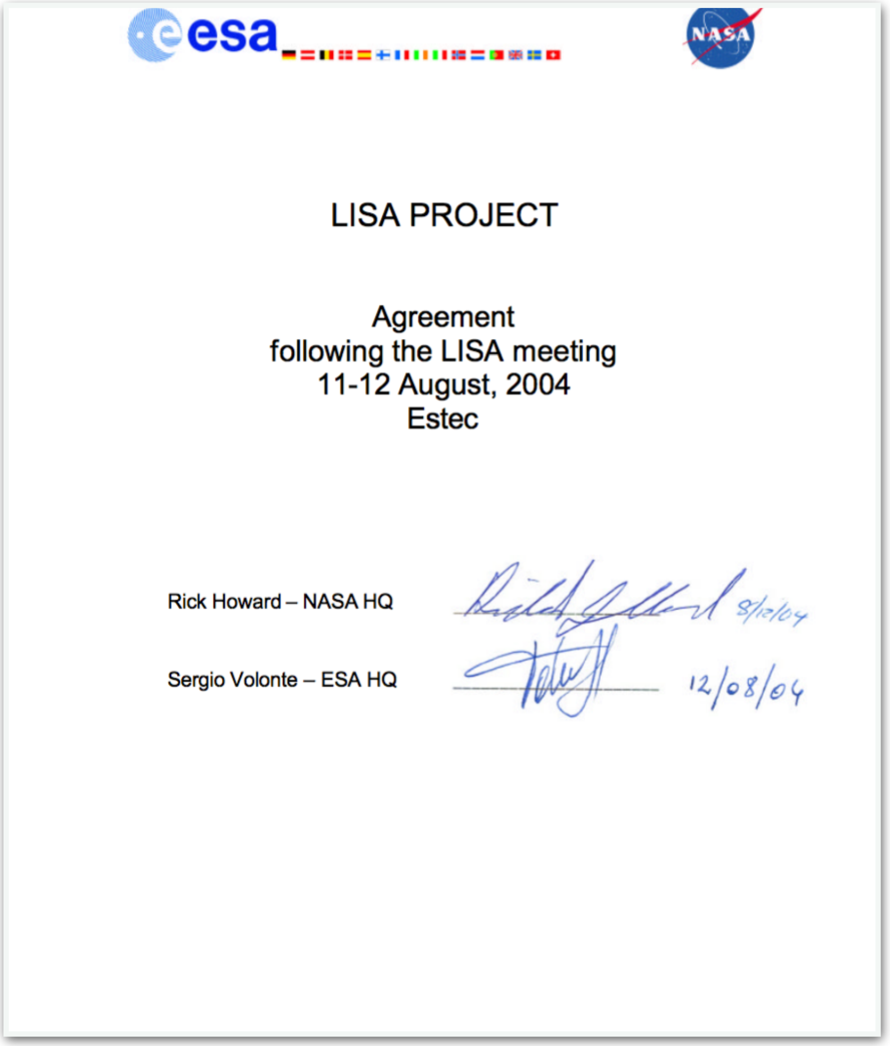
From the Charter

The L3ST shall provide the following:

- Analysis of potential NASA hardware contributions to L3;
- Assessment of the **technology development needed** for potential NASA hardware contributions to L3 including **cost and schedule**;
- Assessment of their total **delivery cost**, **science, and risk consequences;**
- …

Reference point: LISA Project Formulation Agreement

- *ESA develops the three LISA Opto-mechanical Core Systems (LOCS) and verifies them individually*
- *JPL develops the three LISA Instrument Metrology and Avionics Systems (LIMAS), integrates them to the three LOCS and verifies that they function together as a 3-arm interferometer before and after integration onto the spacecraft buses. JPL also supplies LOCS sub-assemblies/components to ESA*
- *GSFC integrates each LOCS/LIMAS assembly onto a spacecraft bus to form a sciencecraft, adds the constellation software, verifies that the three sciencecraft, individually and together, fulfill the performance requirements*
- *Procurement of flight micropropulsion elements will be decided at a later stage depending on technology maturity.*


LISA PROJECT

Agreement
following the LISA meeting
11-12 August, 2004
Estec

Rick Howard – NASA HQ

Sergio Volonte – ESA HQ 12/08/04

Input from GOAT (1 of 2)

LISA-Relevant Technologies receiving some NASA funding in the past several years:

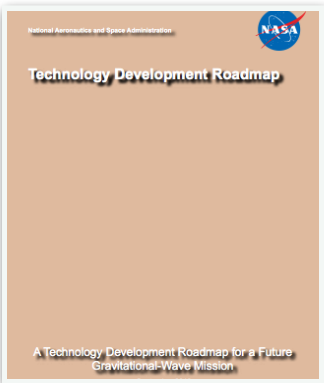
- telescope subsystem
- phase measurement subsystem
- laser subsystem
- micronewton thrusters
- arm-locking demonstration for laser stabilisation
- gravitational reference sensor
- multi-axis heterodyne interferometry (testmass/interferometer interface)
- ultraviolet LEDs for test mass charge control
- optical bench designs to facilitate manufacturing
- inter-spacecraft interferometry demonstration on GRACE Follow-on

Input from GOAT (2 of 2)

"From its inception, the former LISA mission was a productive collaboration among scientists in Europe and the US, striving to achieve the outstanding science promised by the L3 Gravitational Wave mission. The Committee suggests that such a mission will be more robust, and provide a greater science return per euro, if the US could consider a larger contribution, including a re-establishment of a meaningful collaboration currently restricted by funding availability in the US, and the provisional cost cap on non-European participation. The Committee has confidence that ESA can continue leadership in this new scientific frontier while encouraging a larger participation by the US"

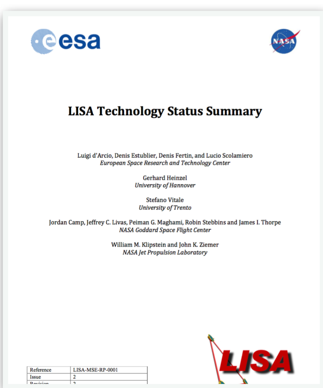
Klipstein: We want to encourage productive collaboration between Europe and the US, beyond just widgets.

Prior Documents



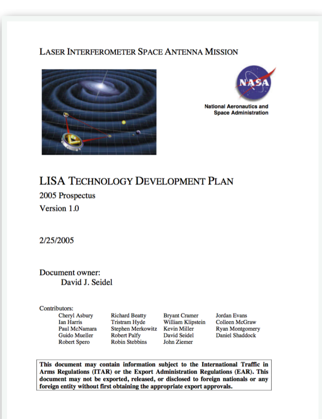
2013 NASA GW Technology Development Plan

- Last major review of LISA technology undertaken in the US
- Presented development estimates for each technology.
- http://pcos.gsfc.nasa.gov/docs/TDR_GW_2013Nov21.pdf



2010 LISA Technology Status Summary

- Last joint NASA/ESA Technology Status Summary
- Assumed Baseline LISA Partnership
- http://lisa.gsfc.nasa.gov/Documentation/LISA-MSE-RP-0001.pdf



2005 NASA LISA Technology Development Plan

- Last formal project development plan with milestones, etc.
- Not available online