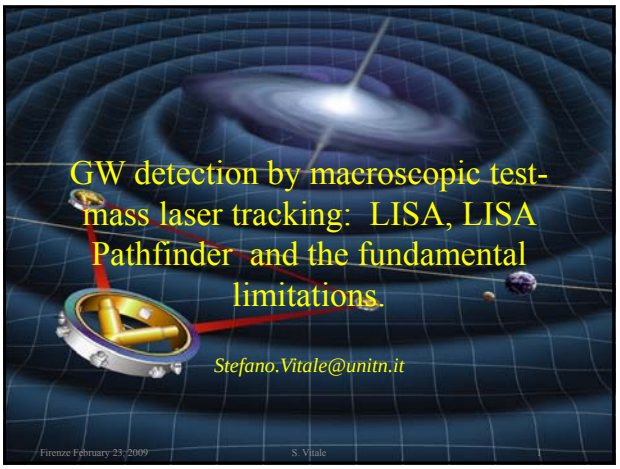
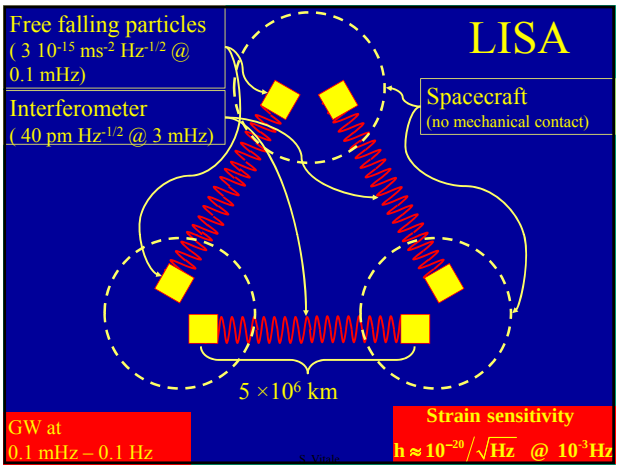
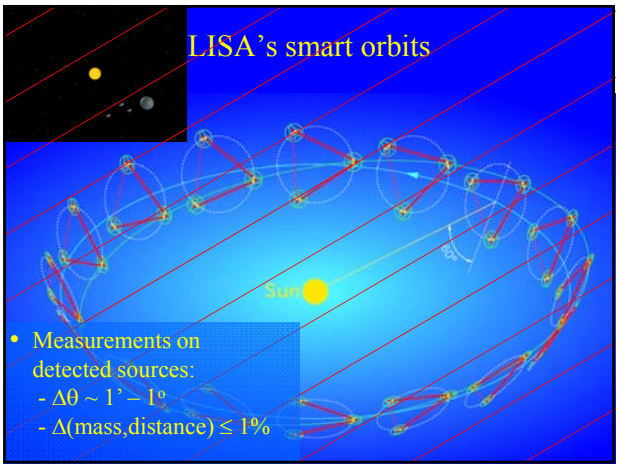
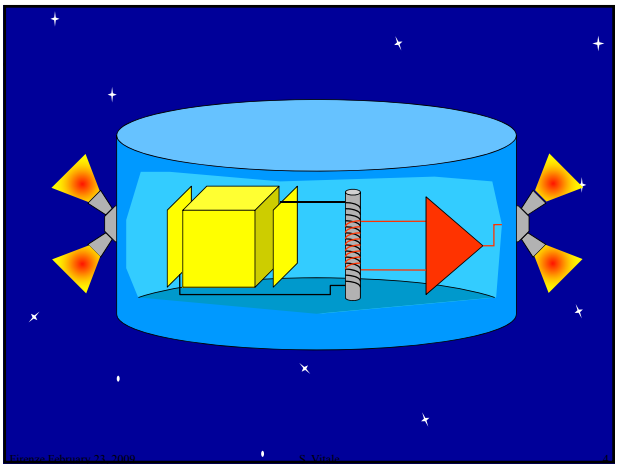
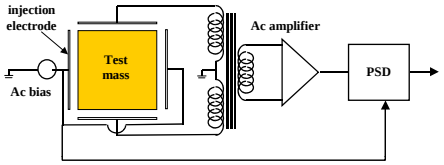

GW detection by macroscopic test-mass laser tracking: LISA, LISA Pathfinder and the fundamental limitations.
Stefano.Vitale@unitn.it
Firenze February 23, 2009
S. Vitale


Free falling particles
(3 10-15 ms-2 Hz-1/2 @ 0.1 mHz)
Interferometer
(40 pm Hz-1/2 @ 3 mHz)
LISA
Spacecraft
(no mechanical contact)
5 ×10⁶ km
GW at
0.1 mHz – 0.1 Hz
Strain sensitivity
h ≈ 10⁻²⁰/√Hz @ 10⁻³Hz

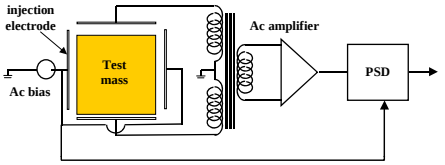

LISA's smart orbits
Sun
• Measurements on detected sources:
- Δθ ~ 1' – 1°
- Δ(mass,distance) ≤ 1%

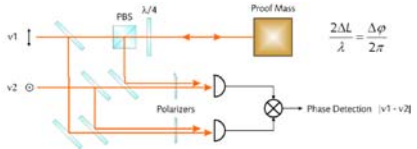


LTP
displacement sensor



LTP
displacement sensor

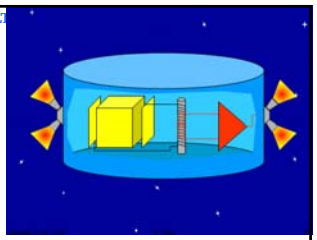


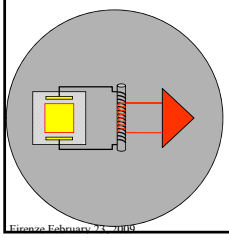


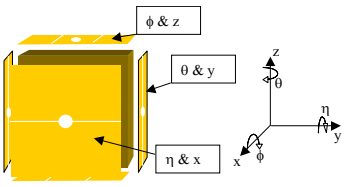
Optical readout along the sensitive axis

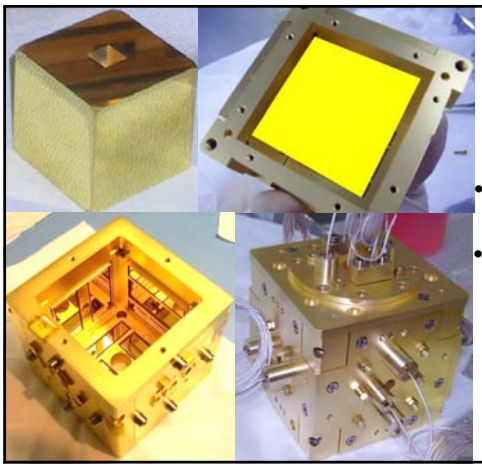
LTP

- Drag-free along sensitive direction
- Test-mass control along the remaining ones

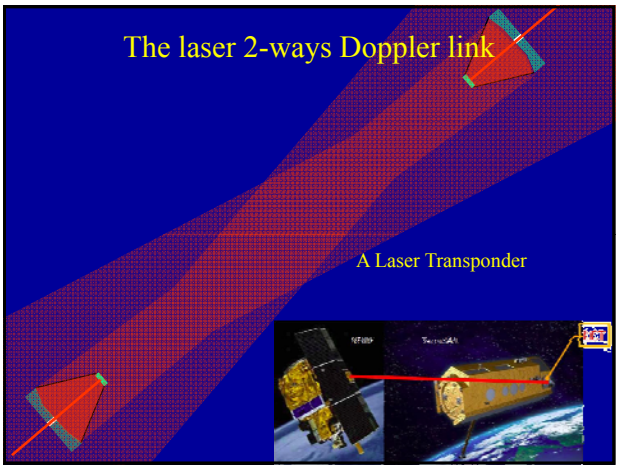


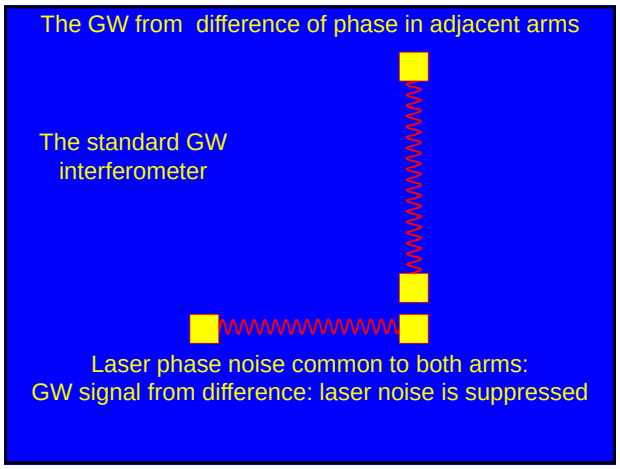


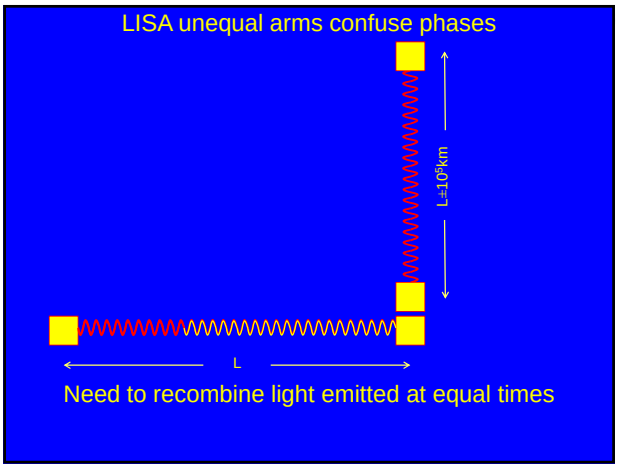


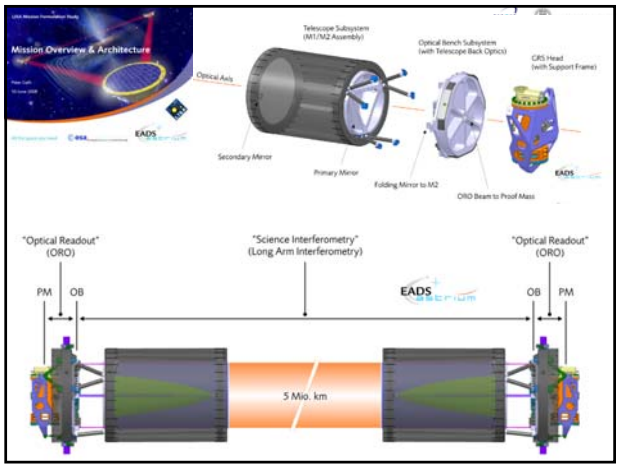


- 2 kg Au-Pt test-mass
- 4 mm gaps

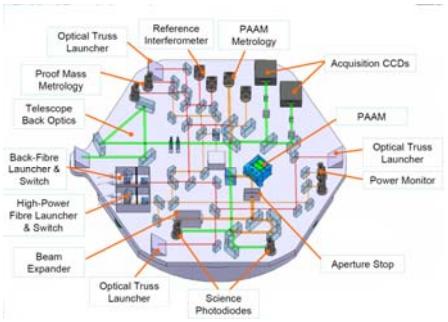

The laser 2-ways Doppler link
A Laser Transponder

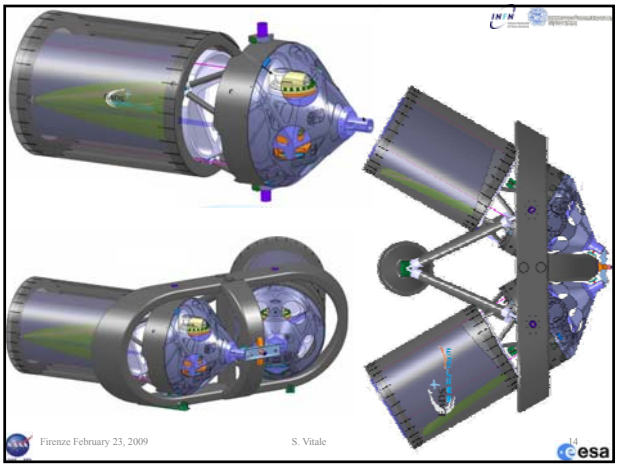

The GW from difference of phase in adjacent arms
The standard GW interferometer
Laser phase noise common to both arms:
GW signal from difference: laser noise is suppressed

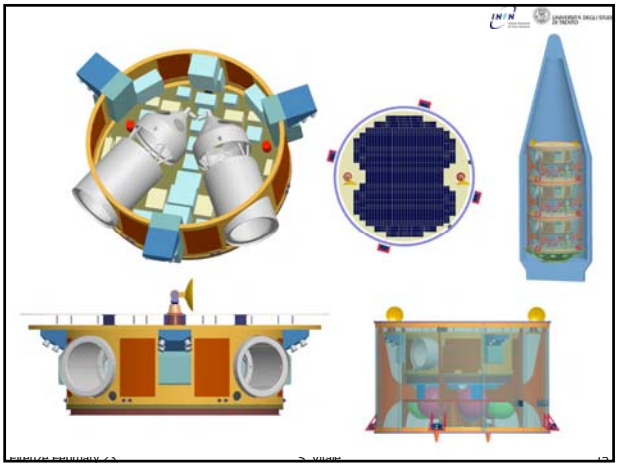

LISA unequal arms confuse phases
L±10%km
L
Need to recombine light emitted at equal times

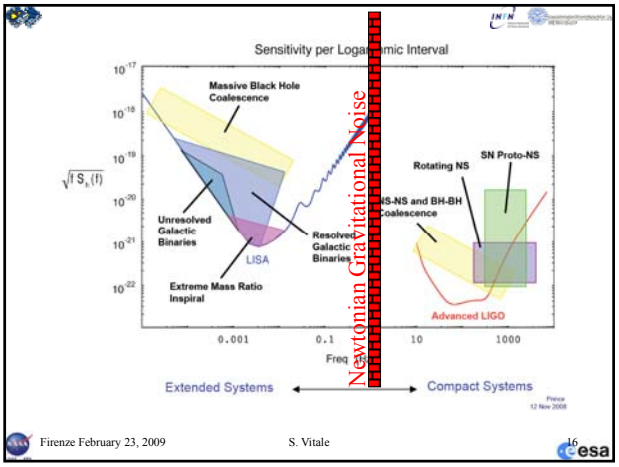

Mission Overview & Architecture
"Optical Readout" (ORO)
"Science Interferometry" (Long Arm Interferometry)
"Optical Readout" (ORO)
PM
OB
EADS
OB
PM
5 Mio. km

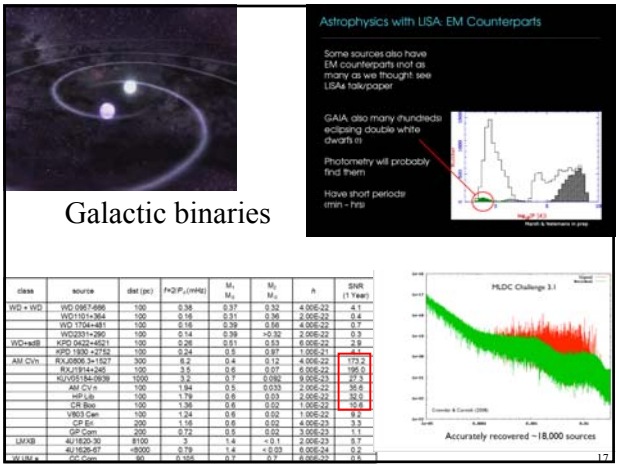
LTP

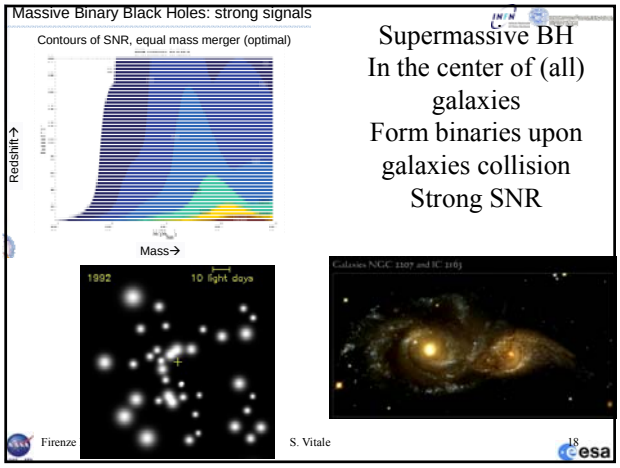

Optical Truss Launcher
Reference Interferometer
PAAM Metrology
Acquisition CCDs
Proof Mass Metrology
Telescope Back Optics
PAAM
Optical Truss Launcher
Back-Fibre Launcher & Switch
Power Monitor
High-Power Fibre Launcher & Switch
Beam Expander
Aperture Stop
Optical Truss Launcher
Science Photodiodes

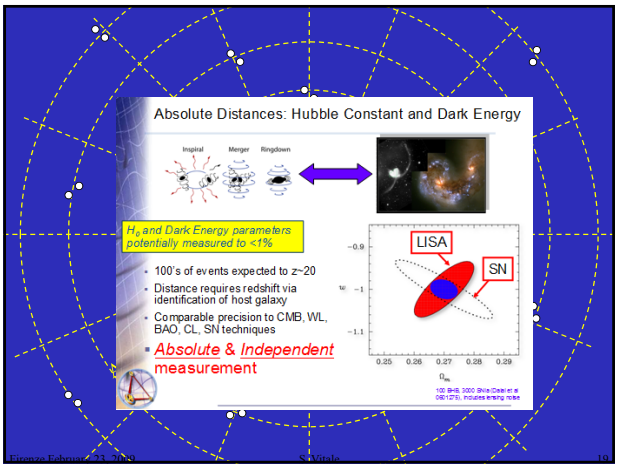


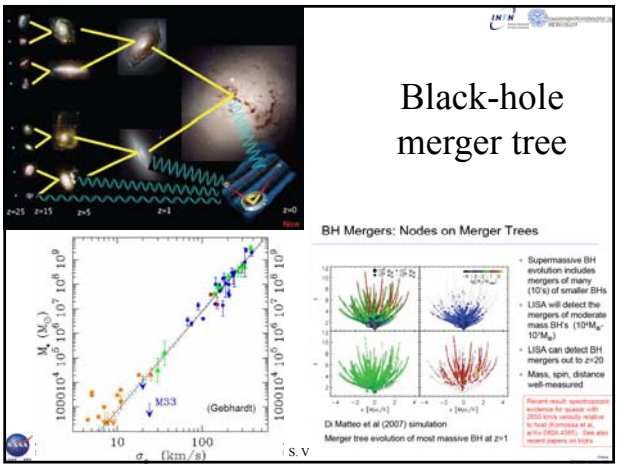


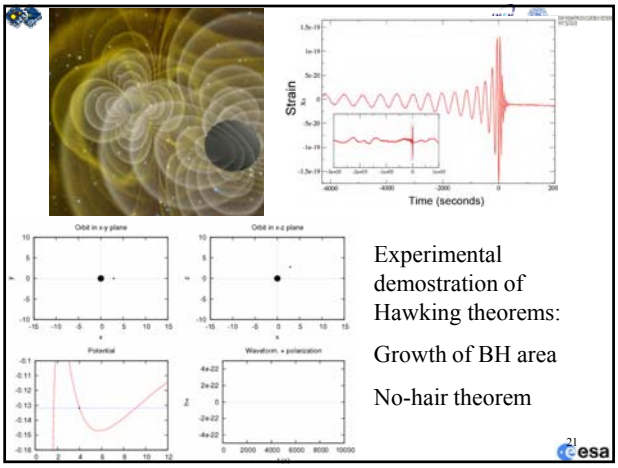

Sensitivity per Logarithmic Interval
Massive Black Hole Coalescence
Unresolved Galactic Binaries
Resolved Galactic Binaries
LISA
Extreme Mass Ratio Inspiral
Rotating NS
SN Proto-NS
NS-NS and BH-BH Coalescence
Advanced LIGO
Freq
Extended Systems
Compact Systems
Newtonian Gravitational Noise


Galactic binaries
Astrophysics with LISA: EM Counterparts
Some sources also have EM counterparts (not as many as we thought see LISAs talk/paper
GAIA: also many (hundreds) eclipsing double white dwarfs (!)
Photometry will probably find them
Have short periods (min - hrs)
MLDC Challenge 3.1
Accurately recovered ~18,000 sources
17


Massive Binary Black Holes: strong signals
Contours of SNR, equal mass merger (optimal)
Redshift→
Mass→
Supermassive BH
In the center of (all) galaxies
Form binaries upon galaxies collision
Strong SNR
1992
10 light days
Firenze
S. Vitale
18
esa


Absolute Distances: Hubble Constant and Dark Energy
Inspiral
Merger
Ringdown
H_0 and Dark Energy parameters potentially measured to <1%
100's of events expected to z~20
Distance requires redshift via identification of host galaxy
Comparable precision to CMB, WL, BAO, CL, SN techniques
Absolute & Independent measurement
LISA
SN
w
Ω_m
Firenze February 23, 2009
S. Vitale
19

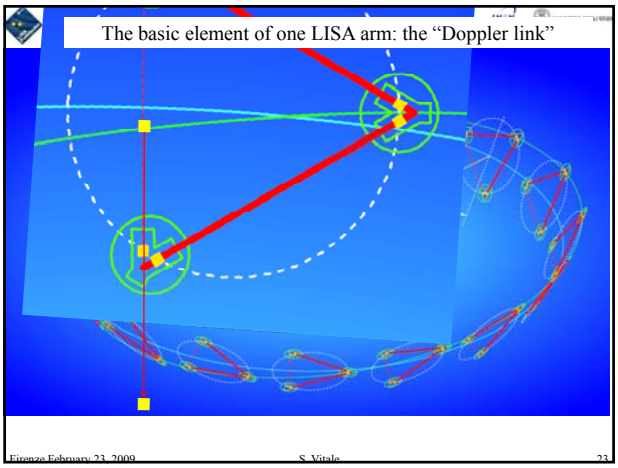

Black-hole merger tree
z=25
z=15
z=5
z=1
z=0
Now
BH Mergers: Nodes on Merger Trees
Supermassive BH evolution includes mergers of many (10's) of smaller BHs
LISA will detect the mergers of moderate mass BH's ($10^4 M_\odot$-$10^7 M_\odot$)
LISA can detect BH mergers out to z=20
Mass, spin, distance well-measured
M33
(Gebhardt)
Di Matteo et al (2007) simulation
Merger tree evolution of most massive BH at z=1
S. V

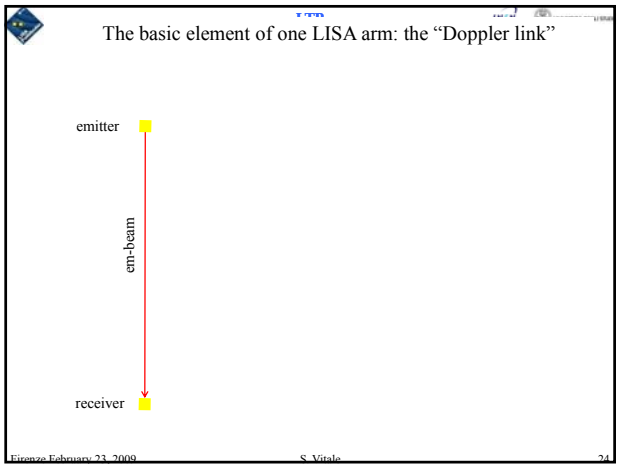


Experimental demostration of Hawking theorems:

Growth of BH area

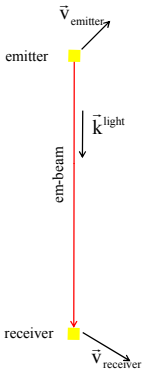
No-hair theorem





LTP

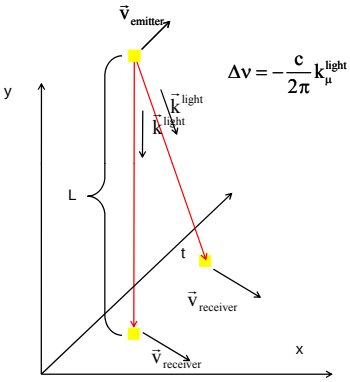
Measuring relative velocity along the line of sight



$$\Delta\nu = -\frac{c}{2\pi} k_{\mu}^{light} \cdot \left(\nu_{emitter}^{\mu} - \nu_{receiver}^{\mu} \right)$$

LTP

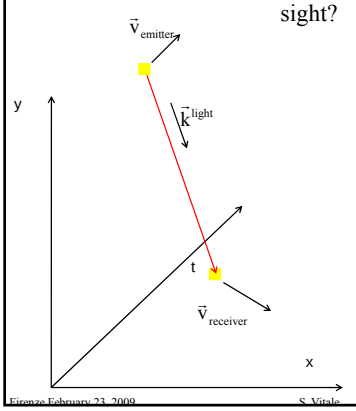
Time delay: to be pictured in space-time



$$\Delta\nu = -\frac{c}{2\pi} k_{\mu}^{light} \cdot \left(\nu_{emitter}^{\mu}(t - L/c) - \nu_{receiver}^{\mu}(t) \right)$$

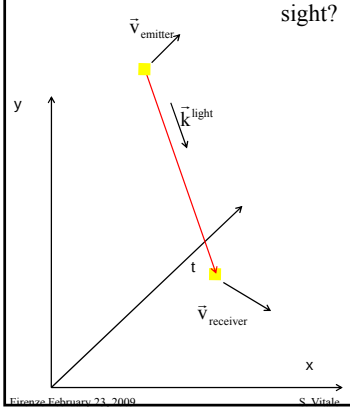
LTP

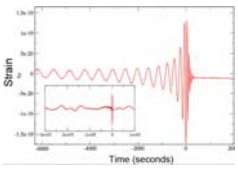
What does change relative velocity along the line of sight?



LTP

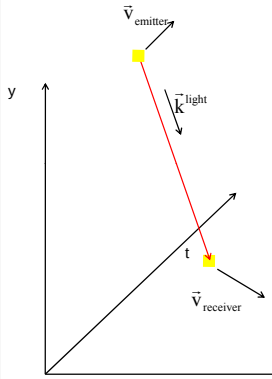
What does change relative velocity along the line of sight?



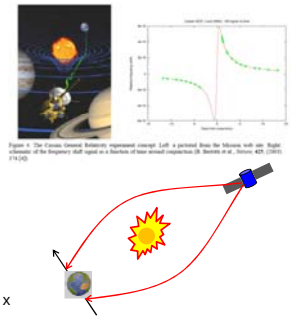


- Gravity:
  - Parallel transport

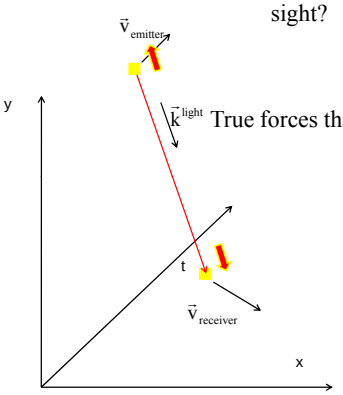
What does change relative velocity along the line of sight?



Rotation of the line of sight

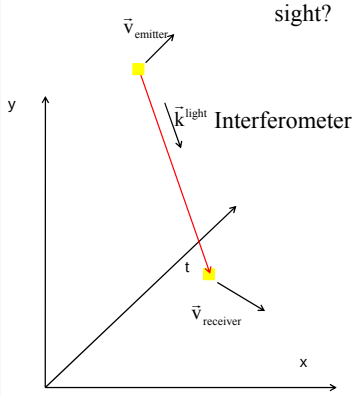


What does change relative velocity along the line of sight?



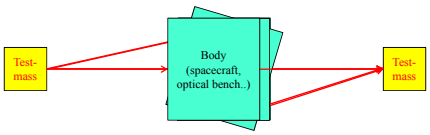
True forces that accelerate test-masses

What does change relative velocity along the line of sight?

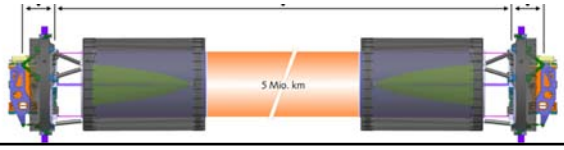


Interferometer measurement noise

The problem of staged links

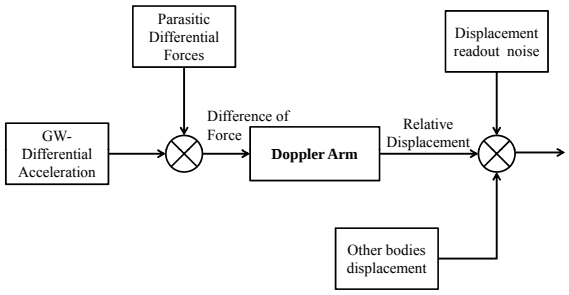


- Links are split as test-masses cannot carry optics
- Perfect split is insensitive to motion of body (bodies)
- Misalignments, calibration errors mix motion of extra bodies in



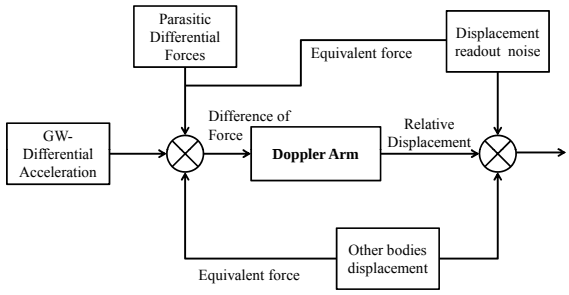
LTP

An Input-Output Description



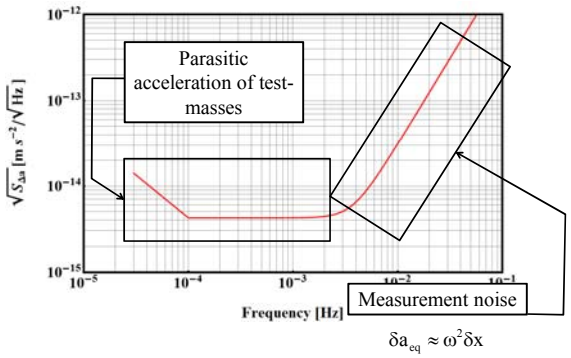
LTP

An Input-Output Description



LTP

Differential acceleration performance

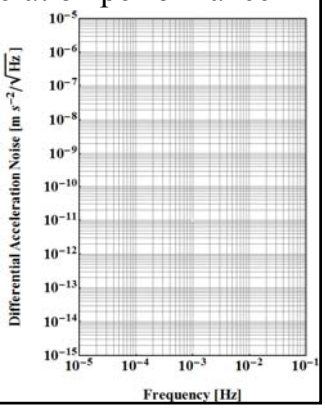


$\delta a_{eq} \approx \omega^2 \delta x$

LTP

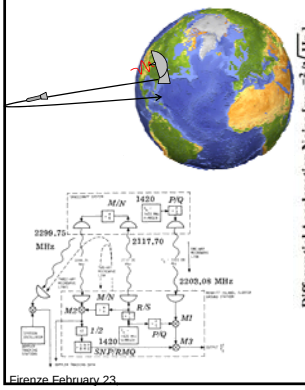
Differential acceleration performance

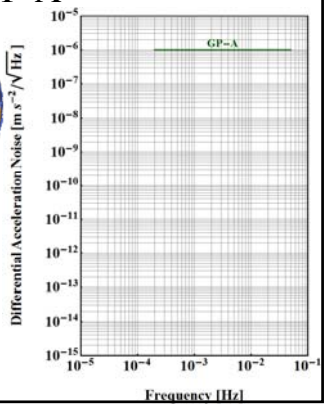
A "Universal" plot



LTP

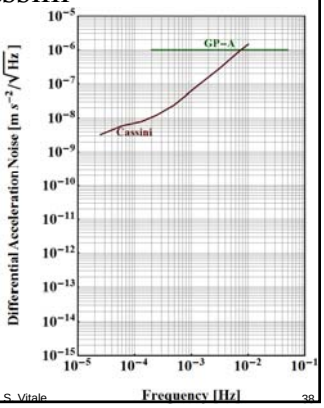
GP-A





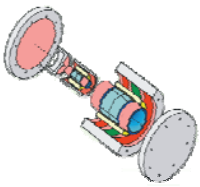
LTP

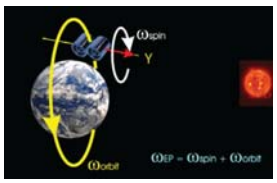
Cassini

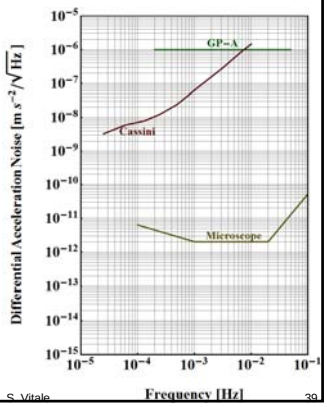


LTP

Microscope

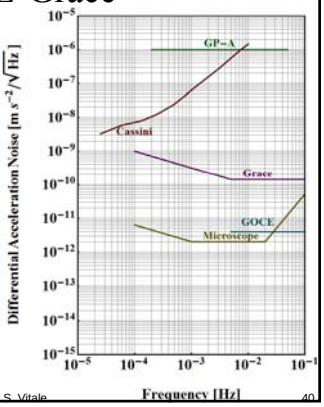


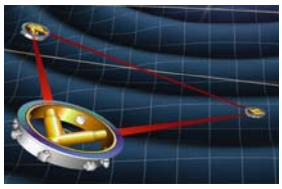


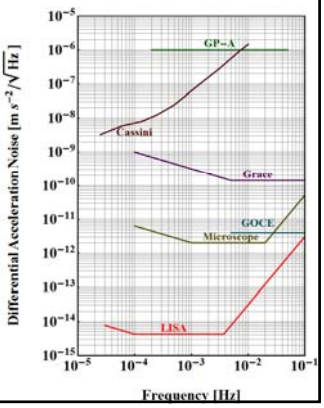


LTP

GOCE-Grace





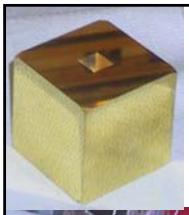


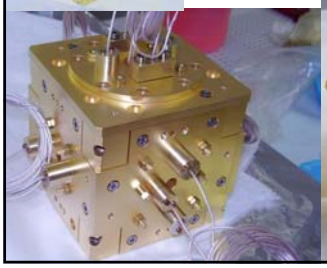
Testing on Ground

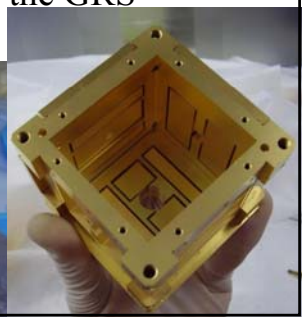
- Surface forces
  - Mostly originated from the nearest surroundings of test-mass
- Volume forces
  - Magnetics
  - Locally generated gravitation

	Budget	Requirement
$a_{Thermal}$	$4.15055 \cdot 10^{-15}$ m / √Hz s²	$4.4 \cdot 10^{-15}$ m / √Hz s²
$a_{Brownian}$	$1.53749 \cdot 10^{-15}$ m / √Hz s²	$1.7 \cdot 10^{-15}$ m / √Hz s²
$a_{MagnEffects}$	$8.85461 \cdot 10^{-15}$ m / √Hz s²	$1.2 \cdot 10^{-14}$ m / √Hz s²
$a_{SideCharge}$	$1.1279 \cdot 10^{-15}$ m / √Hz s²	$1.5 \cdot 10^{-15}$ m / √Hz s²
$a_{LaserRadiation}$	$1.02111 \cdot 10^{-15}$ m / √Hz s²	$4 \cdot 10^{-15}$ m / √Hz s²
$a_{SelfGravity}$	$6.4 \cdot 10^{-14}$ m / √Hz s²	$2.99817 \cdot 10^{-13}$ m / √Hz s²
$a_{StrayVoltage}$	$9.74369 \cdot 10^{-15}$ m / √Hz s²	$1.2 \cdot 10^{-14}$ m / √Hz s²
$a_{Margin,\ Internal}$		$2.053 \cdot 10^{-14}$ m / √Hz s²
Total	$9.20052 \cdot 10^{-15}$ m / √Hz s²	$2.5 \cdot 10^{-14}$ m / √Hz s²
Margin	$2.32454 \cdot 10^{-14}$ m / √Hz s²	

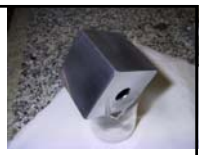
Test-mass nearest surroundings and shield: the GRS

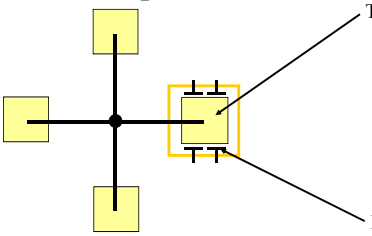






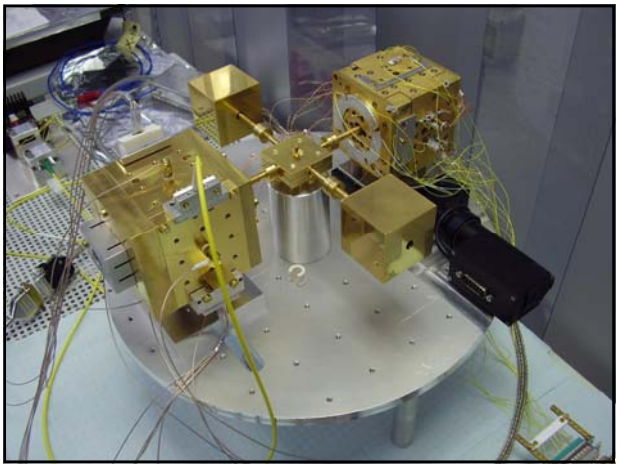
Assessing surface parasitic forces on ground: the torsion pendulum

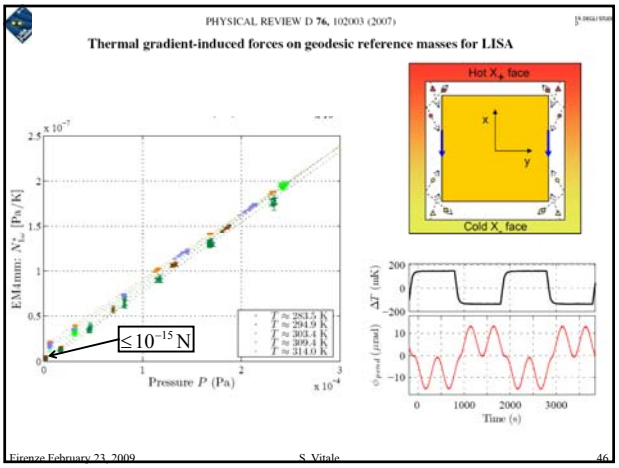


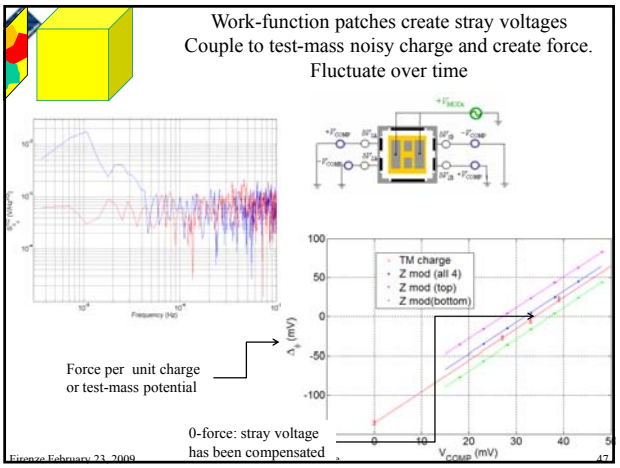


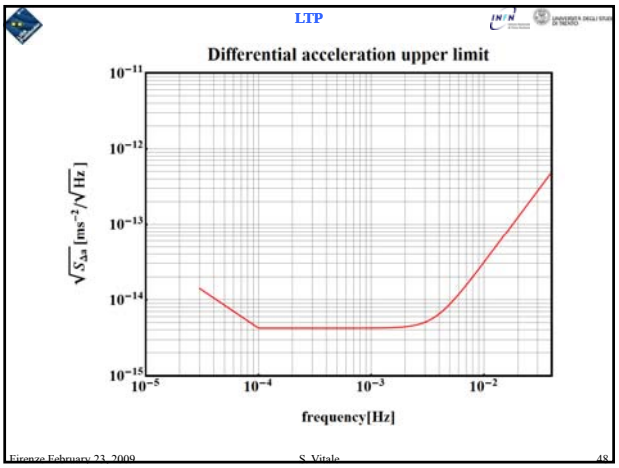
VOLUME 91, NUMBER 15 PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2003

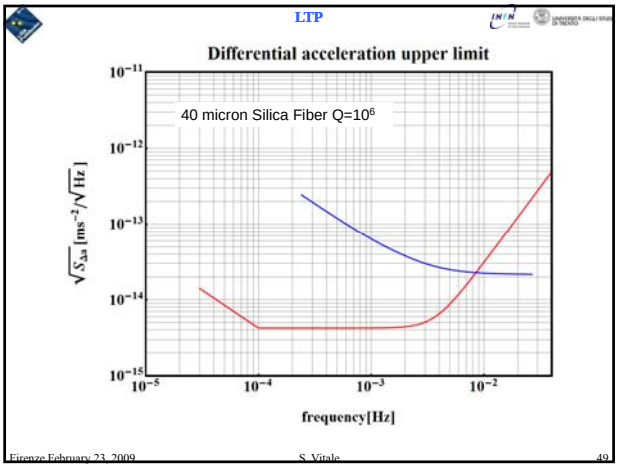
Achieving Geodetic Motion for LISA Test Masses: Ground Testing Results

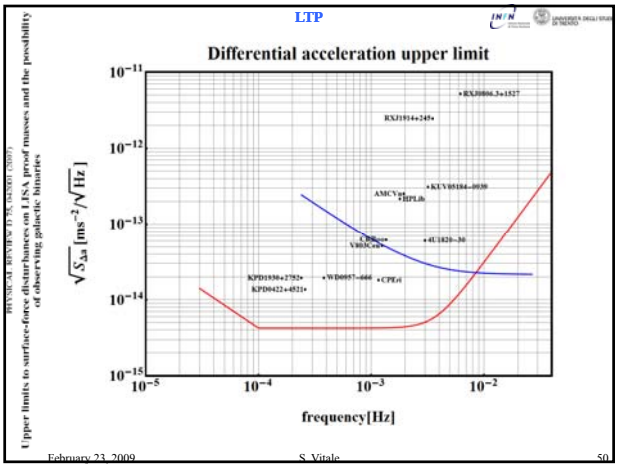


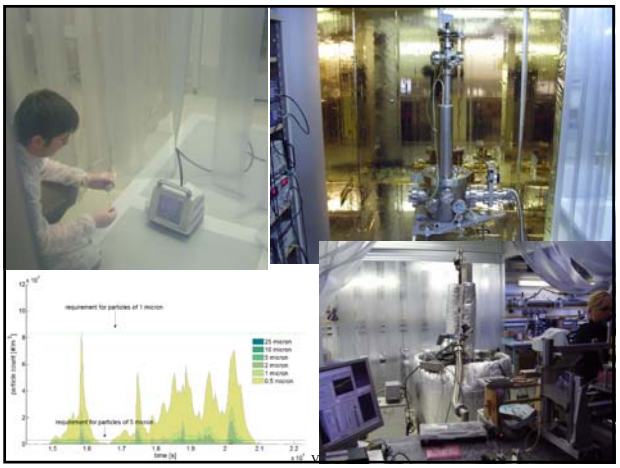

PHYSICAL REVIEW D 76, 102003 (2007)
Thermal gradient-induced forces on geodesic reference masses for LISA
Hot X+ face
Cold X- face
x
y
≤10⁻¹⁵ N
Pressure P (Pa)
Time (s)
Firenze February 23, 2009
S. Vitale
46

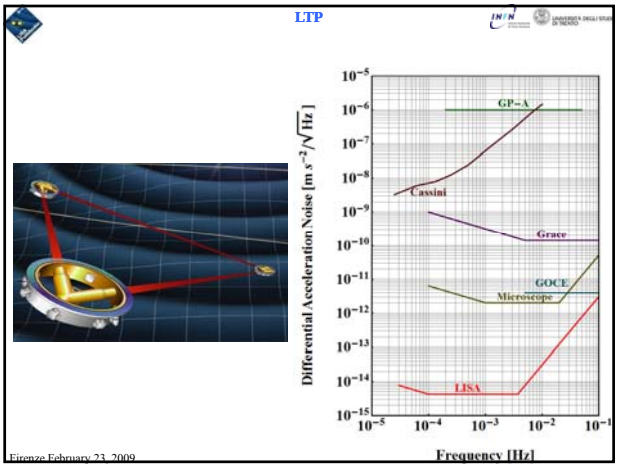

Work-function patches create stray voltages
Couple to test-mass noisy charge and create force.
Fluctuate over time
TM charge
Z mod (all 4)
Z mod (top)
Z mod(bottom)
Force per unit charge
or test-mass potential
0-force: stray voltage
has been compensated
Firenze February 23, 2009
47

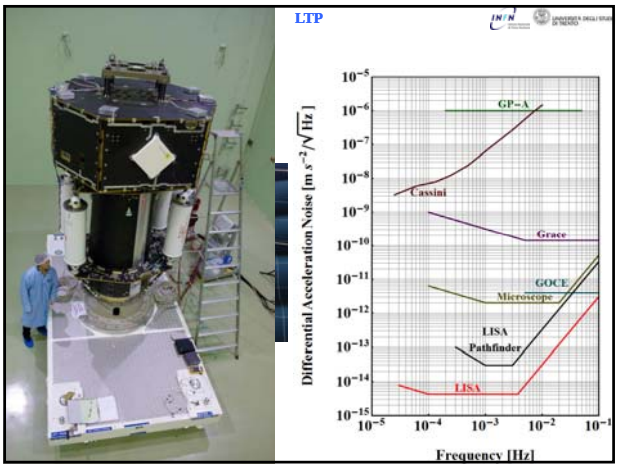

LTP
Differential acceleration upper limit
frequency[Hz]
Firenze February 23, 2009
S. Vitale
48

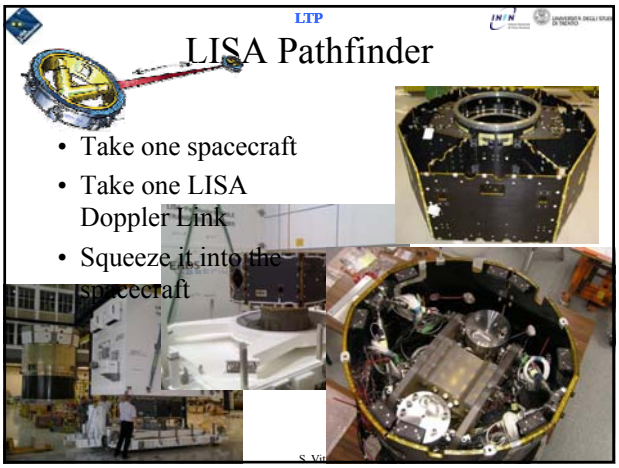

LTP
Differential acceleration upper limit
40 micron Silica Fiber Q=10^6
$\sqrt{S_{\Delta a}}$ [ms^{-2}/$\sqrt{\text{Hz}}$]
frequency[Hz]
Firenze February 23, 2009
S. Vitale
49

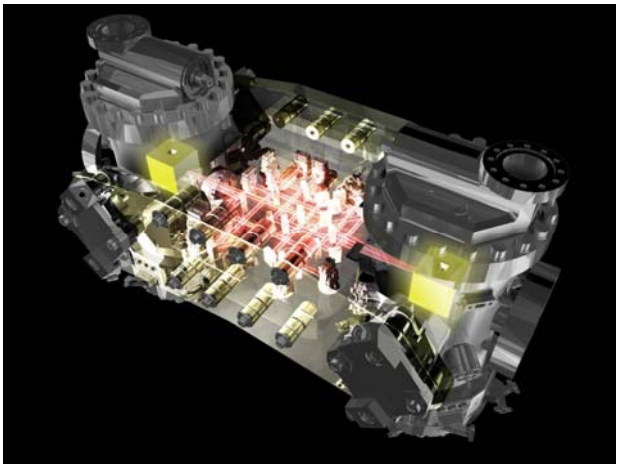

LTP
Differential acceleration upper limit
Upper limits to surface-force disturbances on LISA proof masses and the possibility of observing galactic binaries
$\sqrt{S_{\Delta a}}$ [ms^{-2}/$\sqrt{\text{Hz}}$]
frequency[Hz]
February 23, 2009
S. Vitale
50

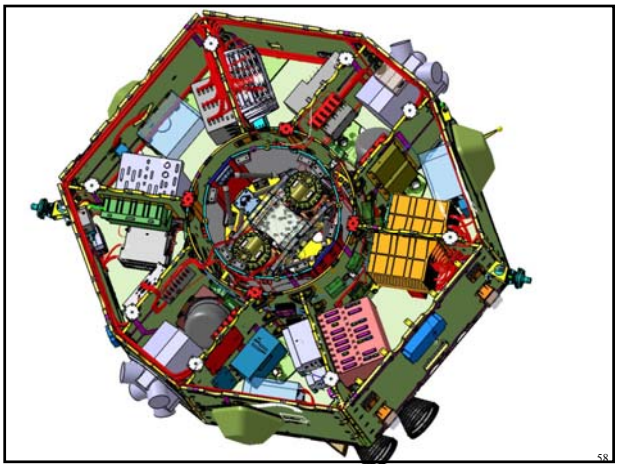


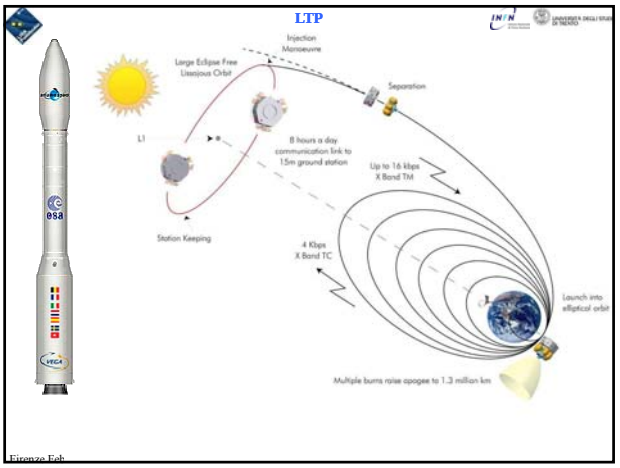

LTP
GP-A
Cassini
Grace
GOCE
Microscope
LISA
Differential Acceleration Noise [m s^{-2}/√Hz]
Frequency [Hz]
Firenze February 23, 2009

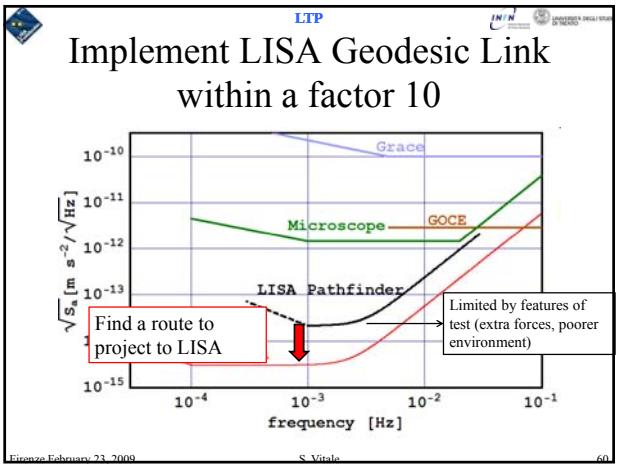

LTP
GP-A
Cassini
Grace
GOCE
Microscope
LISA
Pathfinder
LISA
Differential Acceleration Noise [m s^{-2}/√Hz]
Frequency [Hz]


LTP
LISA Pathfinder
• Take one spacecraft
• Take one LISA Doppler Link
• Squeeze it into the spacecraft





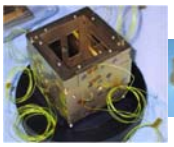

LTP
Injection Manoeuvre
Large Eclipse Free Lissajous Orbit
Separation
L1
8 hours a day communication link to 15m ground station
Up to 16 kbps X Band TM
Station Keeping
4 Kbps X Band TC
Launch into elliptical orbit
Multiple burns raise apogee to 1.3 million km
esa
VEGA

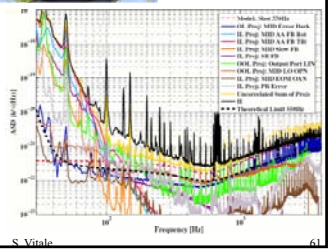

LTP
Implement LISA Geodesic Link within a factor 10
Grace
Microscope
GOCE
LISA Pathfinder
Find a route to project to LISA
Limited by features of test (extra forces, poorer environment)
$\sqrt{S_a}$ [m s^{-2}/$\sqrt{\text{Hz}}$]
frequency [Hz]
Firenze February 23, 2009
S. Vitale
60

LTP

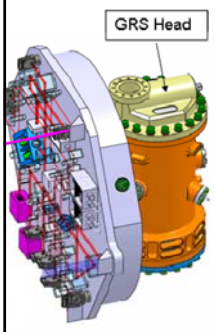
Pathfinder → LISA

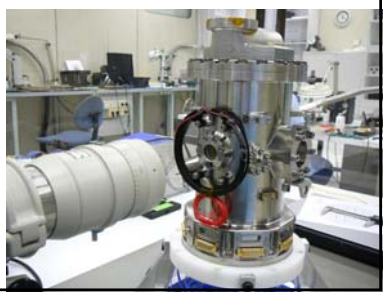
- Fly nominal LISA hardware on Pathfinder:
  - Maximize returns of the test
  - Shortens time to develop LISA
- Identify quantitatively leading sources of noise:
  - Physical model allows extrapolation to LISA
  - Will allow accurate understanding of LISA data

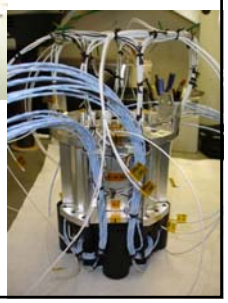




LTP







Practicing routing and packaging

LTP

Gravitational balance

Reduced IBM1			e-9) on TM1 after compen			
Mass [kg]	Cut along Z axis [m]	Cut along Y axis [m]	F_x [s^{-2}]	F_y [s^{-2}]	F_z [s^{-2}]	T
0.55117	-0.034	-0.046	97.77	-72.55	-82.37	
0.53350	-0.04	-0.044	93.56	-66.73	-84.48	
0.55057	-0.038	-0.044	99.69	-70.22	-87.12	
0.56956	-0.036	-0.044	107.28	-74.21	-90.73	
0.52947	-0.044	-0.042	93.40	-62.46	-88.59	
0.54572	-0.042	-0.042	99.35	-66.00	-90.99	
0.56309	-0.04	-0.042	105.69	-69.68	-93.64	
0.52371	-0.048	-0.04	91.54	-57.28	-91.90	
0.54000	-0.046	-0.04	97.84	-61.06	-94.42	
0.55508	-0.044	-0.04	103.43	-64.42	-96.69	
0.52624	-0.05	-0.038	91.22	-53.06	-95.81	
0.54278	-0.048	-0.038	96.66	-55.26	-99.02	
0.56408	-0.046	-0.038	106.81	-62.37	-102.09	
0.54846	-0.05	-0.036	99.07	-53.81	-102.91	

Table 22 Total Gravitational field (...e italic characters are t... the requirements

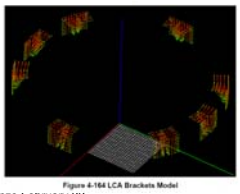


Figure 4-164 LCA Brackets Model

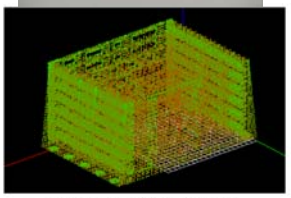
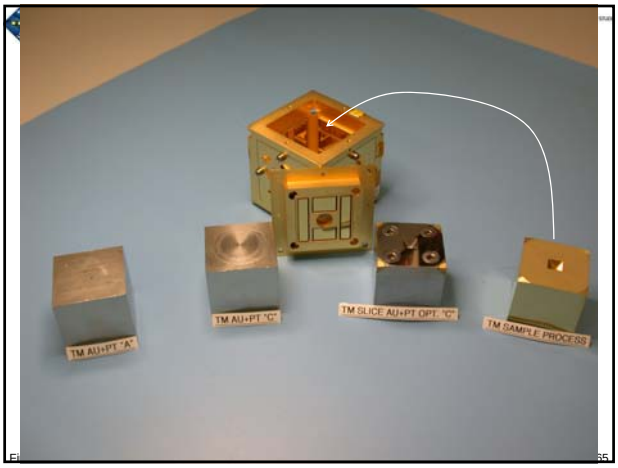
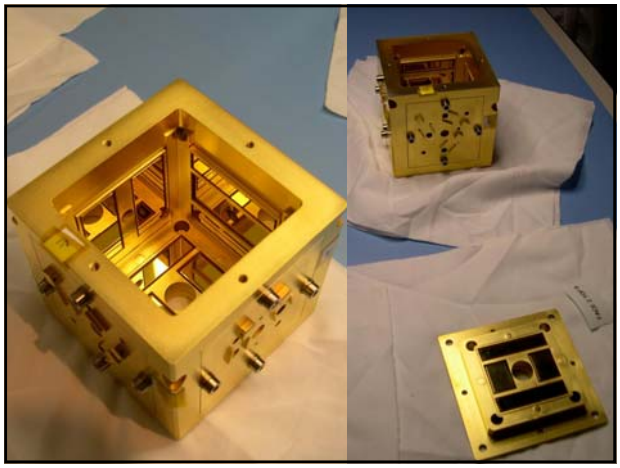
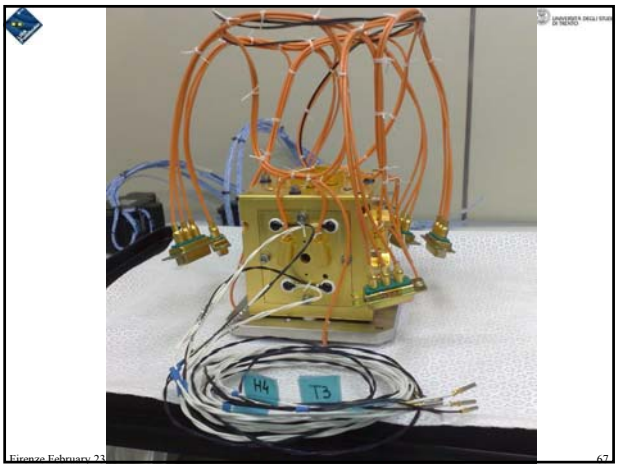


Figure 4-54 Data Management Unit Model

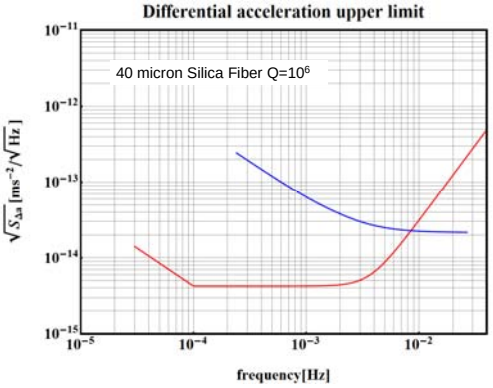

TM AU+PT "A"
TM AU+PT "C"
TM SLICE AU+PT OPT "C"
TM SAMPLE PROCESS



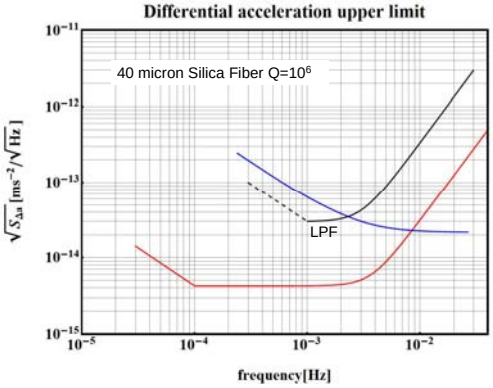

H4
T3


ZEISS

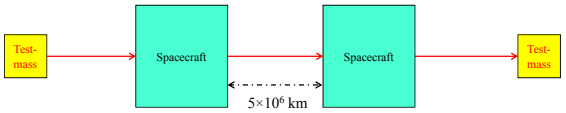
Differential acceleration upper limit



Differential acceleration upper limit

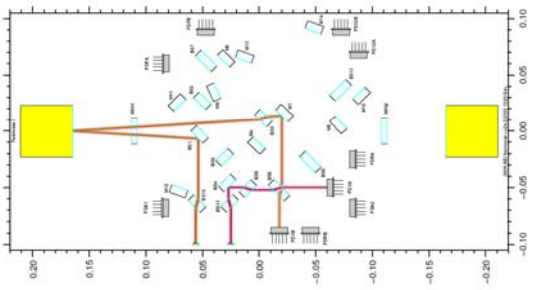


Pathfinder interferometry and the relevance to LISA



- LISA link is 3-stage
- LISA pathfinder has no spacecraft → spacecraft link
- A test of the local interferometric readout for LISA
- A test of the test-mass → spacecraft → test-mass split link

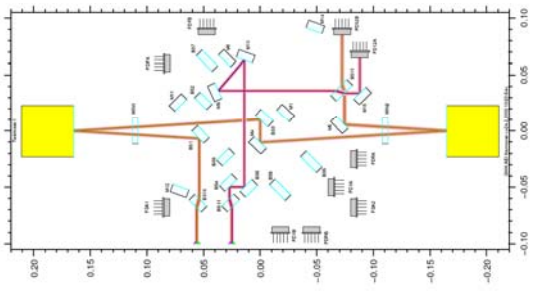
Potential local LISA readout



Albert Einstein Institute

LTP

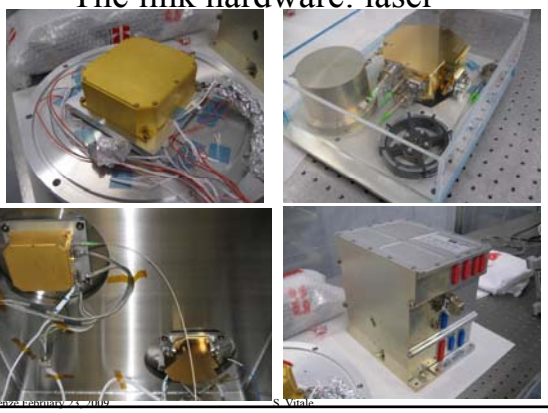
The test-mass ↔ spacecraft ↔ test-mass link

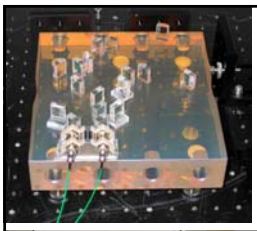


Albert Einstein Institute

LTP

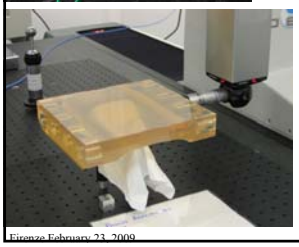
The link hardware: laser



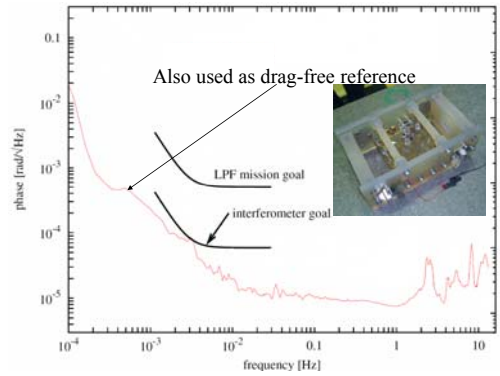


LTP

The link hardware: optical bench



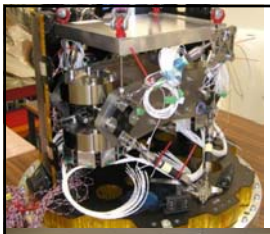
LTP

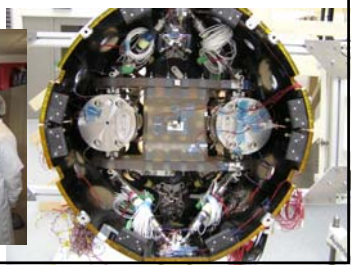


Albert Einstein Institute

LTP

The link hardware: the ultra-stable structure

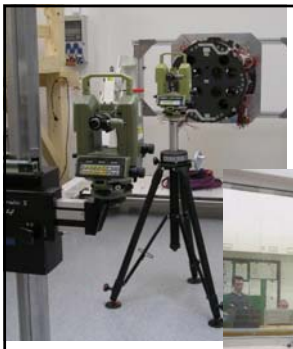


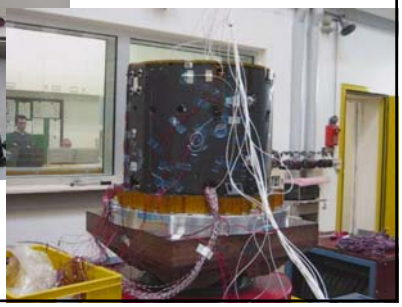


Firenze February 23, 2009

LTP

The link hardware: ultra-stable structure





Firenze February 23, 2009

LISA Pathfinder

esa SCIENCE

Overview of electrical models

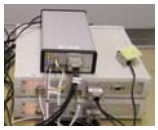
DMU

CCU

LCU

IS FEE (SAU & SSU)

ULU BBR



PMU BBR

1

LISA Pathfinder

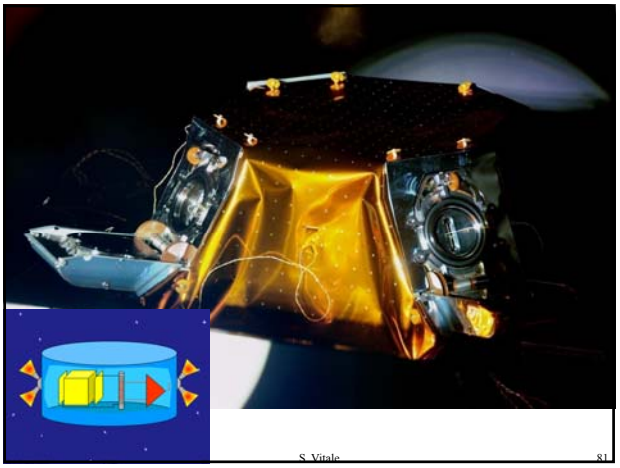
esa SCIENCE

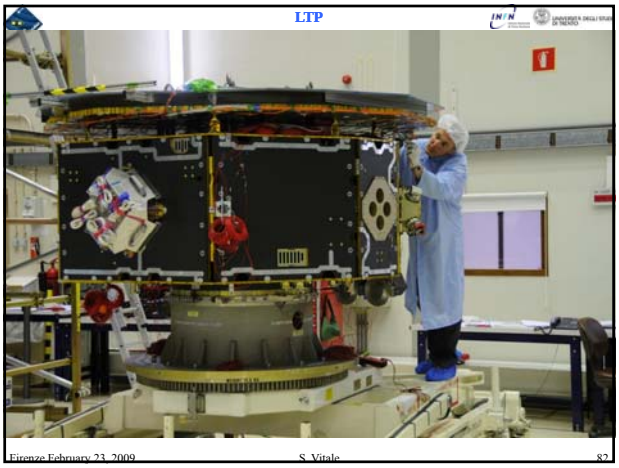
LTP EM flat-bed set-up

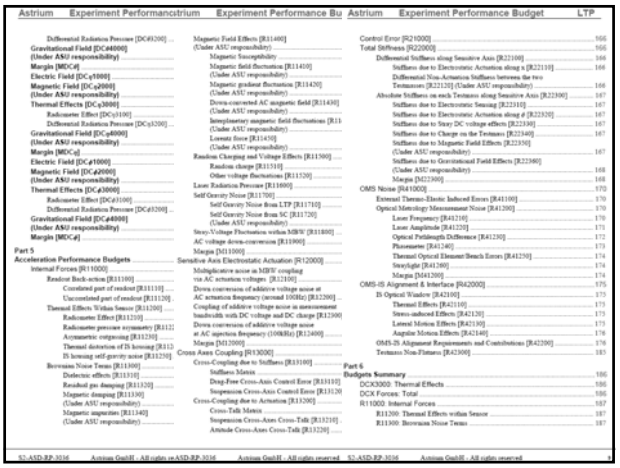
EM Set-up

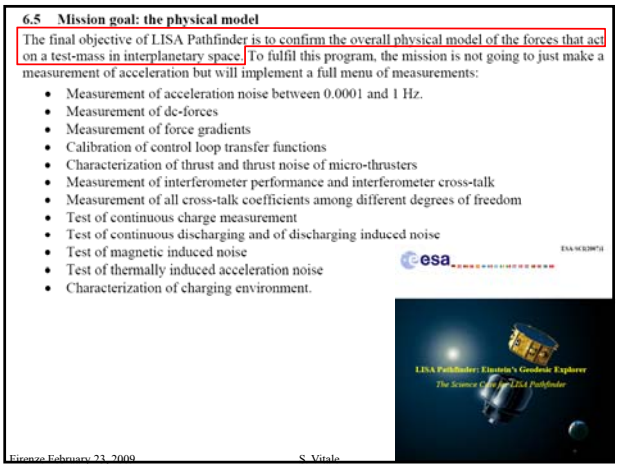
LTP SCOE & OM SCOE

1

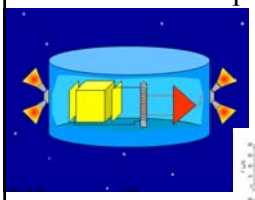



LTP


Astrium Experiment Performancstrium Experiment Performance Bu Astrium Experiment Performance Budget LTP


6.5 Mission goal: the physical model
The final objective of LISA Pathfinder is to confirm the overall physical model of the forces that act on a test-mass in interplanetary space. To fulfil this program, the mission is not going to just make a measurement of acceleration but will implement a full menu of measurements:
Measurement of acceleration noise between 0.0001 and 1 Hz.
Measurement of dc-forces
Measurement of force gradients
Calibration of control loop transfer functions
Characterization of thrust and thrust noise of micro-thrusters
Measurement of interferometer performance and interferometer cross-talk
Measurement of all cross-talk coefficients among different degrees of freedom
Test of continuous charge measurement
Test of continuous discharging and of discharging induced noise
Test of magnetic induced noise
Test of thermally induced acceleration noise
Characterization of charging environment.
esa
LISA Pathfinder: Einstein's Geodesic Explorer
The Science Case for LISA Pathfinder

One example: "spacecraft noise"



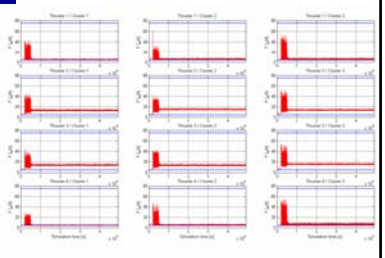
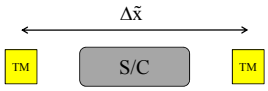
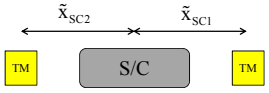


Figure 7-12: Thruster commands (all thrusters available)

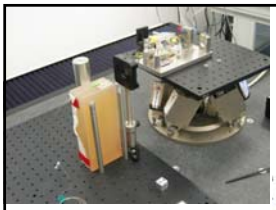
Things are not perfectly differential



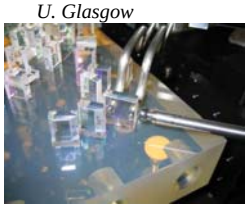
Things are not perfectly differential



$$\Delta\tilde{x} = \tilde{x}_{SC2} + (1+\delta)\tilde{x}_{SC1} \quad = x_2 - x_1 + \delta \times \tilde{x}_{SC1}$$

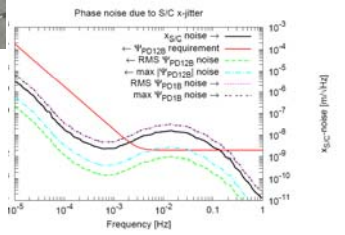


U. Glasgow



Albert Einstein Institute
Max Planck Institute for Gravitational Physics

LTP-OBI-ALIGNMENT SIMULATION



$$\delta \le 10^{-4}$$

The effect of gradients

The effect of gradients

$$g_1 = \omega_1^2 \tilde{x}_{SC}$$

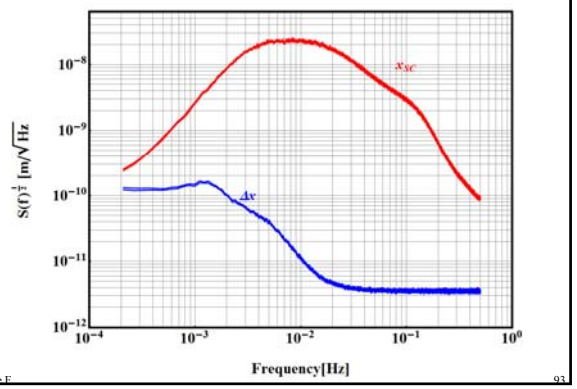
The effect of gradients

Spacecraft jitter accelerates test-mass via gradients

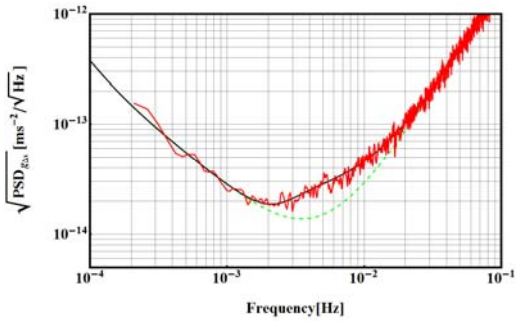
Correcting for Spacecraft Motion

- Spacecraft motion is measured with high resolution (interferometer)
- Effect in differential link can be subtracted

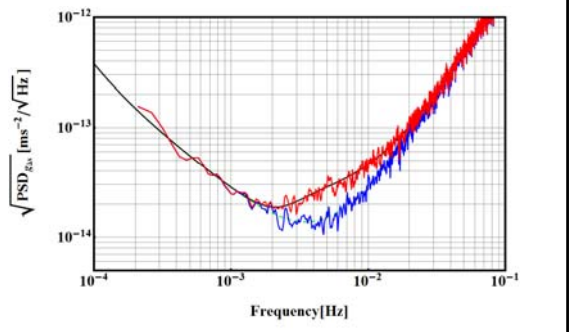
A simulated example

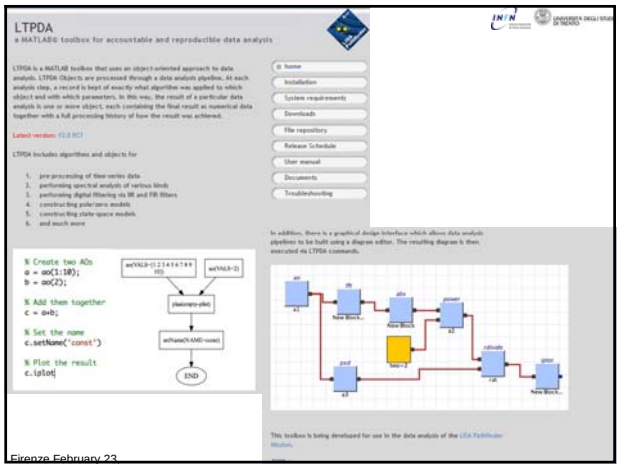


Uncorrected differential acceleration



Corrected for cross-talk and coupling



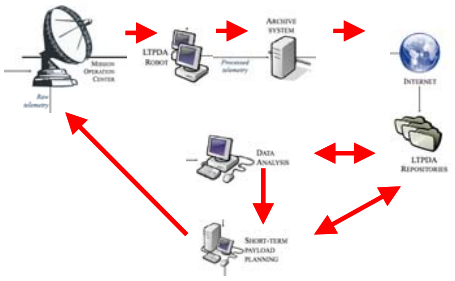


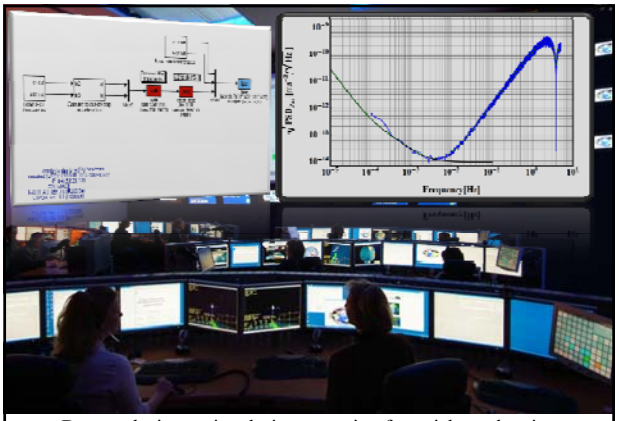
Data analysis

ASCII
Raw data

Analysis Objects
Raw data

Analysis Objects
Processed data

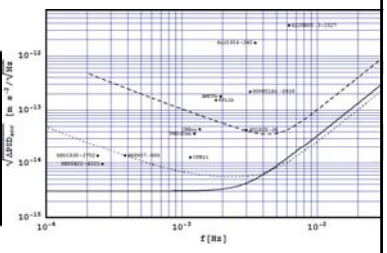




Data analysis running during operation for quick re-planning

LTP

Raising the stake



LISA Pathfinder Science Working Team

Taking into account the uncertainty in the estimate of the various model entries, LISA Pathfinder may be able to put an upper limit on non-modelled disturbances of *the relative acceleration of test-masses* at:

$$\Delta a_{\text{non-modelled}} \approx 7 \times 10^{-15} \left(\text{m/s}^2 \sqrt{\text{Hz}} \right) @ \text{1mHz} \qquad (4)$$