New Sciencecraft and Test Mass Concepts for the LISA Mission

Response to a *Request for Information* for
"*Concepts for the NASA Gravitational-Wave Mission*"
submitted to the *NASA Science Mission Directorate*
Solicitation Number: NNH11ZDA019L

Michael Shao[1] (michael.shao@jpl.nasa.gov), Slava G. Turyshev[1] (turyshev@jpl.nasa.gov),
Nelson Pedreiro[2] (nelson.pedreiro@lmco.com),
Domenick Tenerreli[3] (domenick.tenerelli@lmco.com), Alain Carrier[2] (alain.carrier@lmco.com),
and Suresh Doravari[4] (doravari@caltech.edu)

[1]*Jet Propulsion Laboratory, California Institute of Technology,*
4800 Oak Grove Drive, Pasadena, CA 91109-0899, USA

[2]*Lockheed Martin Advanced Technology Center,*
3215 Porter Drive, Palo Alto, CA 94304-1191, USA

[3]*Lockheed Martin Space Systems, 1111 Lockheed Martin Way, Sunnyvale CA 940891, USA*

[4]*California Institute of Technology, 200 East California Boulevard,*
Pasadena, California, 91125, USA

Summary: We propose a new concept for LISA that removes several major factors of technological risk thereby offering an affordable solution for the NASA's gravitational-wave mission at a significant cost reduction compared to the present design. In particular, we offer new design solutions in the areas that are currently among the chief error sources including disturbance compensation system, test mass design, caging mechanism for test masses, and thermal control system. This is achieved by looking at alternatives for both the instrument design and the spacecraft architecture that are either free from most of the LISA's technical challenges or else have them at a much reduced level. The new LISA concept is based on the novel spacecraft architecture, known as Disturbance Free Payload (DFP) that has been developed by LMSC and recently was successfully demonstrated in experiment. In the new architecture, the payload and the spacecraft are separate bodies that fly in close-proximity formation and interact through non-contact sensors and actuators to achieve precision payload control and isolation from spacecraft disturbances. We propose to replace the cubic test masses currently in the classic LISA design with torsion suspension. The combination of these solutions relaxes many requirements on the performance of various subsystems of LISA architecture, leading to a significant improvement in instrument performance, while reducing the complexity and technological risk for the entire mission. The proposed technologies have reached a significant level of maturity and, most importantly, they lead to a mission design that is entirely testable in ground-based conditions. The total impact on mission's cost that results from relaxation of the key instrument requirements is significant. A mission cost estimate of $990M (FY12$) including 30% reserves, was developed at JPL for a mission with 18 month Phase A/B, 42 month Phase C/D, launch on Falcon 9, 12 month cruise to position, and 5 years of science operations. LISA could be started in 2018 for launch in 2023.

1 Some of the Key Challenges of Current LISA Design

The classic design for the Laser Interferometer Space Antenna (LISA) mission consists of three identical spacecraft flying in a triangular constellation, with equal arms of 5 million kilometers each. LISA will use laser interferometry to detect gravitational waves (GW) from astrophysical sources throughout the Universe at frequencies between about 0.03 mHz and 1 Hz. The mission is designed to be sensitive to the signals with strain of 10^{-23}, which correspond to amplitude below 1 pm (picometer) of displacement between the proof masses separated by 5×10^{6} km.

The required tolerances make LISA technically a very challenging mission, so that a precursor technology feasibility mission, called LISA Pathfinder (LPF), was initiated. However, after a decade in development, currently LPF still has significant technical hurdles. Most of the technical difficulties relate to the performance of the drag-free system proposed for LISA, with two of them adversely impacting LPF. One issue relates to the Caging Mechanism Assembly’s launch lock, which keeps LPF’s test mass in place during launch, isolating it from the launch-induced vibrations. The second, more serious, unsolved problem in LISA Pathfinder is development of the Field Emission Electric Propulsion (FEEP) micro-propulsion system. This is a key technology that still requires a large leap beyond anything ever developed.

Most of the LISA requirements stem from the currently adopted design for the test masses. The design relies on the cubic test masses and uses capacitance sensors to read-out a mass’ displacement signal. The masses are enveloped by six capacitance plates that are positioned at a small distance (~mm) from the test masses. Such small distance is needed because of the inherent non-linearity of the capacitance sensor (i.e., it is inversely proportional to the sensing distance). While technologically it is possible to make the caging mechanism with such tolerances, the mechanism places stringent requirements on the performance of the drag compensation system.

The drag free system uses the cap-sensor signal to sense the position of the spacecraft with respect to the test mass. The same signal is used to drive the micro-N propulsion system on the spacecraft to compensate for any displacements at a nanometer level. There are many sources of acceleration noise in such a configuration, with some of them related to the external environment (solar radiation pressure, magnetic fields, etc.), spacecraft sources of systematic noise (self-gravity, outgassing, thermal recoil forces, patch effect on the test masses, launch lock release mechanism, etc.), and computation systematics (related to the fidelity of the six-degree control algorithms, etc.). Given the size of the circular solar panel and spacecraft mass, the solar radiation pressure will result in an unwanted acceleration signal on the spacecraft of 10^{-8} m/s^2 with variability up to 10^{-4}. As a result, the solar radiation puts a stringent requirement on the performance of the drag-free system on LISA, which must be able to reject this signal down to the level of 10^{-15} m/s^2/sqrt(Hz). There are other sources of acceleration noise, and most of them are driven by the very tight tolerances imposed on the drag-free system.

There is also an issue of having two test masses on each of the three LISA spacecraft. Clearly, at any given moment of time, only one of masses may be considered as a free-falling. The current design attempts to address this issue by placing additional stringent requirements on the position of the test masses relative to each other. This way some sources of noise would appear in common mode, which leads to constraints on the physical size of payload. This is just one of the examples of LISA design where one subsystem drives the complexity of the entire mission.

2 Proposed Solution and New LISA Concept

We propose a new concept for LISA that looks at alternatives for both the instrument design and spacecraft architecture that either free from most of the LISA’s technical challenges or else have them at much reduced level. The thrust of the concept is to remove or significantly relax tolerances on LISA instruments that drive the cost by changing the architecture of the instrument and the spacecraft. The logic behind this approach is simple – when tolerances are relaxed by a factor of 1000, such as, for example, 1 uK vs 1 mK thermal stability, that should have impact on the cost. When complex and precise (nanometer control) servo systems for electrostatic positioning are eliminated, that should impact the cost. The total impact in the overall mission cost resulting from relaxation of the key instrument requirements is significant. Clearly, there are many areas in the current LISA design where such relaxation could lead to a significant impact on cost.

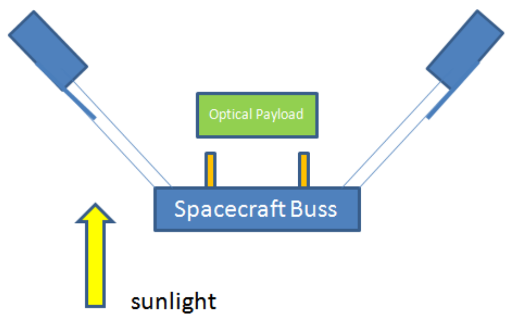

Figure 1 New LISA Concept involving the DFP.

The new LISA concept is based on the novel spacecraft architecture, known as Disturbance–Free Payload (DFP), which has been developed by LMSC (Pedreiro et al., 2002, Pedreiro, 2003; Gonzales et al., 2004) and recently was successfully demonstrated experimentally (Pedreiro et al., 2005; Trankle et al., 2005). In this architecture, the payload and the spacecraft are separate bodies that fly in close-proximity formation and interact through non-contact sensors and actuators to achieve precision payload control and isolation from spacecraft disturbances.

The new concept for the LISA mission still relies on three spacecraft that will be launched by the same launch vehicle and will be placed on the conventional LISA orbits. The proposed spacecraft concept, relying on the DFP, is illustrated in the Figure 1. Each satellite is separated into two modules—an optical-proof-mass payload and a spacecraft bus. The spacecraft bus shields the optical payload (which houses the proof mass) from the sun isolating it from the variable impact of the solar radiation pressure. The optical payload, in the shadow of the spacecraft bus, will passively cool, to ~40K or perhaps even lower for the cavity holding the proof mass.

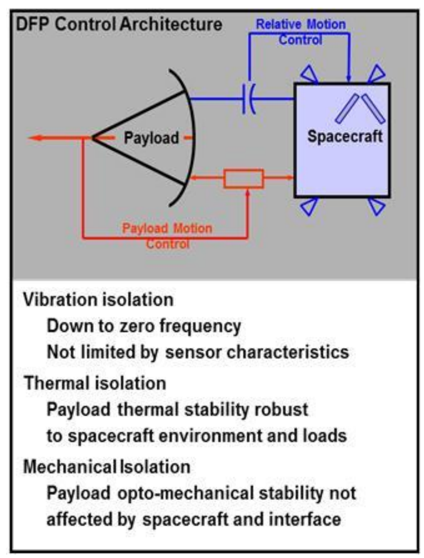

Figure 2 The DFP architecture achieves vibration isolation down to

2.1 *DFP Architecture*

2.1.1 *DFP Control Architecture*

The DFP control architecture is developed to allow controlling the position of a spacecraft with respect to the payload, while providing nearly perfect vibration isolation of that payload from its parent spacecraft down to DC (zero frequency), which is precisely what LISA needs.

We are proposing a pure DFP implementation for LISA that has demonstrated six degree-of-freedom vibration isolation exceeding 60 dB. Aside from the bracketry and the travel stops, the interface between the spacecraft and the payload required for science operation consists of six non-contact electromagnetic actuators in a hexapod configuration and six non-contact relative position sensors also in a hexapod configuration.

2.1.2 Drag Free Control

Drag free control of the LISA payload is achieved by monitoring the position and the orientation of the spacecraft relative to that payload and feeding back that information to the thrusters so as to maneuver the spacecraft to follow the payload.

In the new LISA concept, the spacecraft shields the payload from external force disturbances such as solar radiation pressure, thruster plume impingement, outgassing, and thruster-induced vibrations. There are no mechanically-induced or control-feedback-induced coupling mechanisms resulting in payload disturbances in that architecture because the spacecraft and the payload are mechanically disconnected and the relative position sensor outputs are not fed to the interface actuators. In fact, the significant detrimental interactions between the spacecraft and the payload only come in through gravitational and electro-magnetic field interactions and non-contact power transfer.

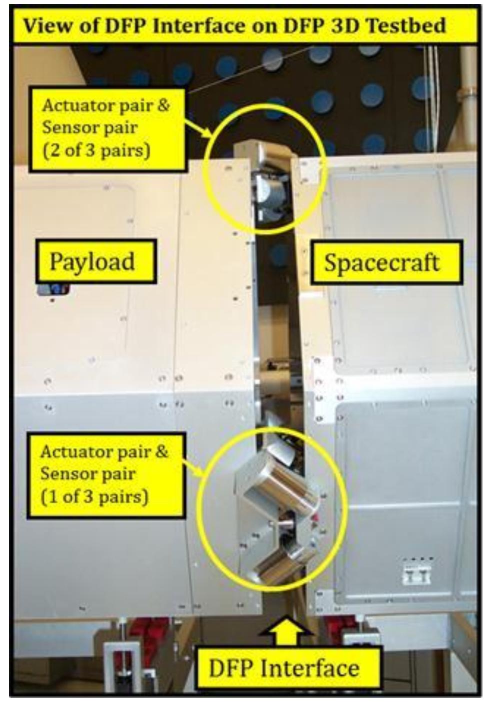

Figure 3 We propose a scaled-version of the proven DFP architecture for LISA

2.1.3 Range of travel and beneficial impact of proposed architecture on thruster selection

In contrast to the classic LISA, the allowable range of travel between the spacecraft and the payload required for drag free science operation is not actuator limited in our proposed architecture. In our case, the range of travel depends primarily on the resolution of the thrusters being selected and the maximum tolerable change in the acceleration of self-gravity acting on the test mass as the spacecraft moves relative to the payload.

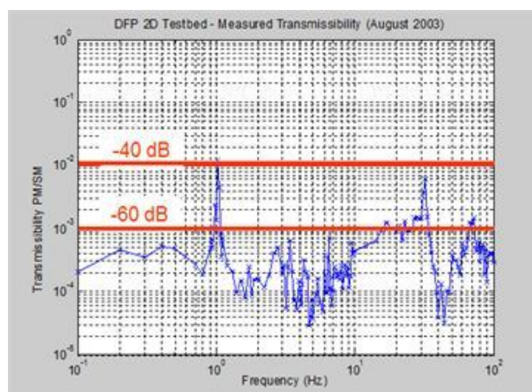

Figure 4 DFP has demonstrated 60dB of vibration isolation down to 0.1 Hz.

We estimate that the change in the forces acting on the spacecraft due to the changes in the solar radiation pressure over time scales of 1000 seconds is on the order of 0.2 nN: our ability to position the spacecraft relative to the payload is therefore limited by the resolution of the thrusters. Assuming a 0.2 Hz position control bandwidth, we estimate that the error in positioning each spacecraft relative to its test mass using the FEEP thrusters in the classical LISA is about 1 nm (1-σ) based on the force noise spectrum data of the FEEP thrusters from Alenia Spazio, which translates into a required range of travel of about 10 nm assuming 5-sigma excursions.

Within our proposed concept, we estimate that we can increase the allowable range of travel between the spacecraft and the payload to 1 μm within the constraints on the change in the acceleration of self-gravity due to the spacecraft acting on the test mass. Since the range of travel required for drag free control is directly proportional to the magnitude of the thruster force noise spectrum for a given shape of that spectrum that increase in available travel from 10 nm to 1 μm translates directly into more forgiving requirements on the thruster force noise by a factor of 100.

2.1.4 Relative position sensor selection

In our architecture, the goal of the drag free control is to maintain the spacecraft to within 1 μm of the payload in any direction (compare it to 1nm needed for classic LISA design). We propose non-contact inductive probes for the purpose of monitoring the position of the spacecraft relative to the payload such as the 15N inductive probe from Kaman Instrumentation. That sensor has sub-nanometer resolution over a 1-Hz bandwidth and a range exceeding 1-mm. That sensor has flight heritage and has the additional benefit of being compatible with operation at cold temperatures down to 4 K, if necessary.

2.2 Payload Pointing Control

The payload pointing control is achieved by monitoring the telescope pointing with the LISA interferometer and feeding back that information to the DFP actuators. We envision a very low bandwidth control loop of 1 mHz or less to implement that function to avoid feeding pointing sensor noise as significant acceleration disturbances within the measurement band of the instrument. The LISA 40-cm telescope can measure pointing of the telescope with a precision at the level of sub-milliarcsecond/sqrt(Hz). The pointing performance will be driven by the accuracy and noise of the LISA optical system. We expect that there will be an ample margin in meeting the LISA pointing requirements.

2.3 Power and Data Transfer

After launch and deployment there will be no physical contact between the spacecraft bus and the optical payload. The bus will fly a drag free orbit using the optical payload as a reference and the attitude (angular orientation) of the optical payload will be controlled using a variant of the DFP, disturbance free payload, concept by LMCO.

Data and commands from the spacecraft bus to the optical payload will be transferred optically. Power ~100W will be transmitted from the spacecraft bus to the optical payload by LED’s or laser diodes on the spacecraft bus and solar cells on the optical payload.

The acceleration imparted to a 50-kg payload due to the associated radiation pressure under that scenario is $\sim 7\times 10^{-9}$ m/s^2 assuming 100-Watt of collimated power is being transmitted. This effect can be mitigated by transmitting power from opposing directions perpendicular to the plane of the LISA laser beams so as to reduce to net steady state portion of that payload acceleration and to reduce the disturbance acceleration in the sensitive directions of the LISA interferometer.

Power fluctuations in the direction of the LISA laser beams would need to be less than 10 μW over time scales of 1000 seconds to bring the induced payload accelerations to within a reasonable fraction of the allowable LISA test mass acceleration budget in the LISA sensitive axes.

If the power transfer is perpendicular to the LISA laser beams to within 1 milliradian, the ~100W optical power transfer only has to be stable to 10 milliwatts (on ~1000 sec time scale).

2.4 Thermal control: passive cooling

Being in the shadow, the optical payload will passively cool to ~ 50K. The radiometer effect is an unwanted acceleration of the proof mass from radiation pressure when one side of the cavity is 1 micro-K hotter than the opposite side; this provides a spurious acceleration of the proof mass by an amount equal to the GW signal. At 50K the radiation pressure is 1000 times less meaning thermal control is needed at ~ 1 mK instead of 1 micro K. The importance of reducing the thermal stability requirement by a factor of 1000 impacts the cost not just in the design and build of the spacecraft, but also in testing the spacecraft.

2.5 Test mass – torsion flexure

We propose to use a torsion pendulum instead of a free floating proof mass. The classic LISA concept relying on a free floating proof mass has a significant number of technical difficulties some of which have not been successfully addressed in LISA Pathfinder, even at its current 400 million euro budget. One of the most difficult issues remains the "caging" mechanism. Should the proof mass accidentally touch one of the electrodes in the walls of the cavity, there is a chance it will be stuck forever because at that point there is no way to control the proof mass's position. Such a possibility is still not being successfully addressed in the current LISA design, presenting serious changes for the entire mission.

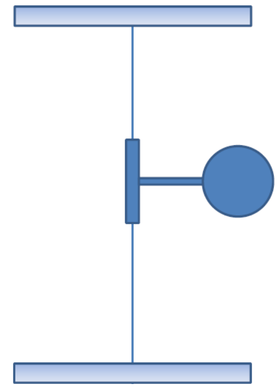

Figure 5 Sketch of a torsion flexure proposed as a proof mass for LISA instrument.

We propose to use a torsion flexure (1 arm of a torsion pendulum, see Figure 5) instead of the free-floating masses to address the problem above. One can think about an accelerometer as being a mass on a spring and a displacement sensor that is measuring the mass's position. To detect mHz gravitational waves the spring has to be very-very soft. Most springs that have the required softness would also be extremely fragile. Torsion pendula used by the group in the University of Washington (Gundlach 2004) have a mHz resonance and can support a several kilogram proof mass in 1g. The problems that do not exist in a torsion pendulum version of LISA are numerous.

a. *Ultra-weak electrostatic control* (which is needed when the proof mass is freely floating vs grounded electro-static forces are orders of magnitude weaker). The ultra-weak control is why the "caging" mechanism for LPF is so challenging. When the "proof mass" is released, its velocity has to be less than 10 micron/sec for LISA, so that it never touches the wall before the electrostatic system grabs hold of it.

b. *Patch effects*. The walls of the cavity holding the proof mass have electrodes to measure the position of the proof mass with sub-nm precision. The electrical potential of these electrodes may have spurious electrical fields known as patch effects. We can reduce the patch effects by 2−3 orders of magnitude, if we don't use cap-sensors.

c. *Cosmic rays*. High energy particles will ionize the proof mass and cause it to accumulate an electrical charge. An on board UV lamp is used to discharge the accumulated charge in Gravity Probe B (GPB) and LPF. Not needed when the proof mass is grounded.

d. Complexity of *6 degree of freedom (DOF) control* of proof mass. The proof mass's position and 3 Euler angles have to be measured and controlled. In a torsion pendulum the proof mass only has 1 degree of motion (at low frequency). That motion can be damped magnetically (passively). The 6 DOF servo control with nanometer accuracy could be replaced with an electro-magnet. The torsion pendulum's motion after "un-caging" has to be damped. In LISA/LPF, this is done under servo control. With the torsion pendulum turning on an electro magnet will cause motion of the proof mass to produce an eddy current that damps out the motion. Eddy current damping would be turned off after the initial oscillation caused by uncaging the proof mass has damped.

There are several reasons why this concept was not possible earlier. Thus, i) making a spring soft enough was a significant challenge; ii) Clearly, a mechanical spring will have some damping. That damping together with 300K temperature gives rise to thermal noise in the suspension. We now have fibers that have extremely high Q’s much higher than normal spring steel or BeCu springs. In addition, we’ll operate at temperatures of the order of 50K and not at 300K!, and iii) Thermal noise of the suspension is less serious at higher frequencies. As a result, this version of LISA would operate above 0.06 mHz. Above 0.06 mHz thermal noise of the suspension would be less than 1e-15m/s^2/sqrt(Hz).

Figure 6 Proposed LISA Clamp Assembly for restraining the proof mass during launch.

2.6 New LISA launch lock and release mechanism

The LISA launch lock and release pivot mechanism includes pin pullers, heater circuits, clamp assembly and tensioner. Figure 6 shows a fabricated, TRL 6, version of the clamp assembly; it is capable of providing high clamp force. The proposed new LISA launch lock is much easier to build, as the release velocity needs to be slow enough not to break the fiber.

The required clamping force depends on the size of the proof mass and the magnitude of the launch loads. The preloaded mechanism is held closed against the proof mass by a flight proven wax actuated, off the shelf, pin puller, shown in Figure 7.

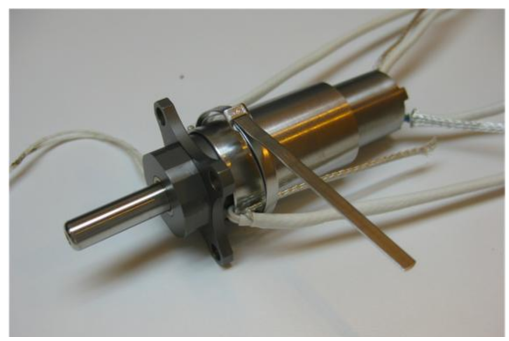

Figure 7 Proposed LISA wax activated pin with redundant heaters.

The tensioner part of the system is to tighten the proof mass torsional pendulum after launch. Post launch tensioning of the pendulum low frequency torsion spring prevents damage to the spring due to structural vibration during ascent. The tensioner is actuated by a preloaded spring and wax actuated pin puller (same as clamp assembly).

3 *Error budget summary*

The LISA error budget published in Stebbins et al (2004) lists the 17 largest error sources that result in unintentional acceleration of the proof masses. The vast majority of these are made smaller with this LISA architecture. While improving sensitivity is one possibility, the other is to relax the requirements on the instrument and spacecraft to make LISA more affordable. LISA is a multiple order of magnitude advance on many technologies, the most critical of which were to be tested by LPF. One of the goals of this architecture is to use technologies that can be tested on the ground at close to the levels needed for the LISA mission.

Some of the largest contributors to the error budget are self-gravity, thermal control, and performance of the test mass. We will discuss some of them below and will offer our solutions.

3.1 Self-gravity

The motion of the spacecraft exerts gravitational attraction to the test mass. To keep contribution of this this error source small, LISA has to fly with respect to a test mass to less than ~10 nm. This implies very precise thrust control that is possible only with the FEEPs. The FEEPs are designed to provide the thrust to counteract variations in solar radiation pressure and the solar wind. One can think of the FEEPs as a single stage vibration isolation system.

Our alternative approach is based on a 2 stage isolation system. The two stage system is based on the Lockheed disturbance free isolation system. A spacecraft bus using cold gas (rather than FEEPs) is positioned between the sun and the optical/proof mass payload. If the spacecraft bus is placed ~1m from the proof mass, then flying the spacecraft bus with 1 micron tolerance would be sufficient to keep self-gravity effects below 3e-15 m/s^2.

3.2 Thermal Noise of a torsion pendulum in space and its performance

There are several advantages in operating a torsion balance in space; chief among them is the ability to support large masses on relatively thin fibers. We can therefore have very low resonant frequencies even as low as the lower limit of the LISA detection band, which would lead to a suppression of thermal noise at higher frequencies as given in (Saulson, 1990). Wherein the equation 16 giving the power spectral density of positional fluctuations is reproduced below

$$\mathrm{PSD}[\omega] = \frac{4k_b T k \varphi}{\omega((kI\omega^2)^2 + k^2\varphi^2)}$$

where k is the torsion constant of the fiber φ (=1/Q) is the loss angle due to dissipation, I is the moment of inertia of the mass on the pendulum, T is its temperature and k_b is the Boltzmann's constant. Due to the very low gas density in interplanetary space, the dissipation in the pendulum chiefly arises only from the internal losses within the flexing member, namely the torsion fiber. We therefore propose to use low loss silica fibers coated with gold, which have a Q of about 10^4 (Gundlach 2004; Gundlach et al 2006). The gold coating is needed to provide electrical conductivity which would avoid charge build-up on the proof mass.

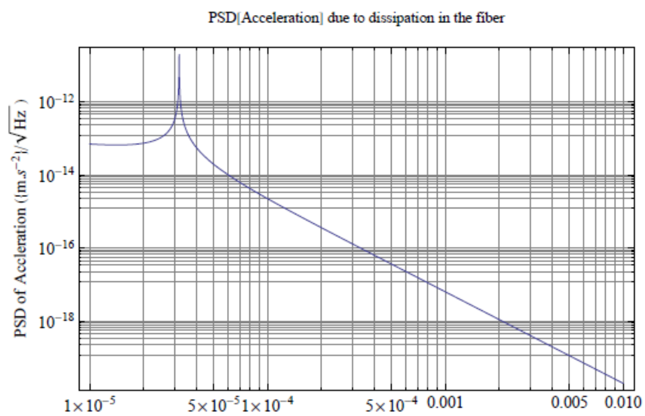

Figure 8 The acceleration noise of a torsion pendulum due to dissipation in the fused silica fiber. Calculated for a pendulum period of about 30,000 s with a Q of 10^4.

For a pendulum consisting of a 1kg mass at the end of a 25cm long arm, attached to a fused silica torsion fiber of about 20cm long and 10 microns in diameter we get a period of about 31,000 s. The acceleration noise spectrum due to its thermal noise is shown in Figure 8.

The maximum acceleration such a fiber would be able to tolerate would be about 1 mm/s^2. As seen above such a pendulum would have acceleration noise less than 1e-15 m/s^2 above 0.2 mHz.

3.2.1 Adopt new laser technology as it becomes available

Laser technology is advancing independent of any LISA effort. The main advances are in higher power, shorter wavelengths, and better frequency stability. Photon noise is the limit at higher frequencies and as laser technology improves, this should be incorporated in any future LISA.

4 Science Objectives for the New LISA Concept

The science objectives of the new LISA concept discussed here are identical to the LISA's current objectives (shown in Table 2 of the RFI, not presented here). In short, in terms of science, the new LISA is the classic LISA mission that will support all the science areas suggested by the LIST. Thus, the new LISA concept will be able to measure signals from the following source types: massive black hole binaries, intermediate-mass black holes, extreme-mass ratio inspirals, close binaries of stellar-mass compact objects; it might also detect signals from cosmological backgrounds, and unforeseen sources (all shown in Table 2 of the RFI).

5 Rough Order-of-Magnitude (ROM) Cost Estimate

The cost estimate presented in this document does not constitute an implementation-cost commitment on the part of JPL or Caltech. The estimate was prepared without consideration of potential industry participation and was derived using a combination of parametric estimates and analogies to comparable historical mission actual costs. The accuracy of the cost estimate is commensurate with the level of understanding of a Pre-Phase A mission concept.

Table 1. ROM cost estimate ($M, FY12).

WBS	Dev	Ops	Total	Notes
PM/PSE/SMA	99	32	131	historical mission average wrap rates
Science	11	64	75	Dev based on *MSL*; Ops based on *Spitzer*
Payload	167		167	Delta off "old LISA" cost + PRICE model
Spacecraft	242		242	SSCM + PRICE model; includes ATLO
MOS/GDS	9	68	77	Dev based on *MSL*; Ops based on *Spitzer*
Launch vehicle	59.5		59.5	SpaceX published cost for Falcon 9
E/PO	3	7	10	1% of total, excluding Reserves and LV
Reserves	181	48	229	30% Ph. A-D, exclude. LV; 15% Ph. E-F
Total ROM	**783**	**207**	**990**	

The new LISA Phases A-F cost estimate is $990M (FY12), which includes the launch vehicle and five years of science operations. All aspects of the mission have a technology readiness level (TRL) of 6 or higher. The cost estimate is provided in Table 1and is based on the following methodology and assumptions:

- *Project Management (PM), Systems Engineering (PSE), Safety & Mission Assurance (SMA).* The cost is calculated as 13.5% (4% PM, 4.5% PSE, 5% SMA) of the payload, spacecraft, ATLO cost. The %age is based on comparable historical mission averages; MSL is 11.3%.
- *Science*. The development portion of the cost (Phases A-D) is calculated as 2.7% of the payload, spacecraft, and ATLO cost, based on MSL actuals. The operations cost (Phases E-F) is $12.8M per year for data analysis, based on Spitzer actual costs.
- *Payload*. The instrument cost is developed using available cost estimates for "old LISA" with deltas subtracted to account for new LISA design normalized to the MSL actual costs. The estimate was then validated using PRICE-H calibrated to MSL to ensure reasonableness.
- *Spacecraft*. The spacecraft cost was developed using the Small Satellite Cost Model (SSCM) normalized to the MSL actual costs and then scaled for the partial redundancy and higher mass and power required for LISA. The estimate was then validated using PRICE-H calibrated to MSL to ensure reasonableness.
- *Mission Operations Systems/Ground Data Systems*. The development portion of the cost (Phases A-D) was calculated as 4.5% of the payload, spacecraft, and ATLO cost. The percentage is based on the MSL actual costs. As LISA will be an observatory, similar in to Spitzer, the operations cost (Phases E-F) is based on the Spitzer actual cost of $13.6M/year.
- *Launch Vehicle (LV).* The mass of LISA is within 5,500 kg or ~60% of the Falcon 9 capability for a either Cape Canaveral AFS or Kwajalein launch.

Acknowledgment:
The work described in this report was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

Gonzales, M., N. Pedreiro, K. Brookes and D. Roth, “Unprecedented Vibration Isolation Demonstration Using the Disturbance- Free Payload Concept”, AIAA Guidance, Navigation, and Control Conference (2004), paper #AIAA-2004-5247, (2004).

Gundlach, J. H., “Torsion Balance Measurement of Forces Between Closely-Spaced Surfaces”, presentation at 38th ESLAB Symposium 5th International LISA Symposium, July 12-15 2004, http://www.rssd.esa.int/SP/SP/docs/LISASymposium/J.Gundlach/Jens_Gundlach.pdf

Gundlach, J. H.,: AIP Conf. Proc. -- November 29, 2006 -- Volume 873, pp. 189-193

Pedreiro, N., A. Carrier, K. Lorell, D. Roth, G. Shelef and R. Clappier, “Disturbance-Free Payload Concept Demonstration”, AIAA Guidance, Navigation, and Control Conference (2002), paper # AIAA-2002-5027, (2002).

Pedreiro, N., “Spacecraft Architecture for Disturbance-Free Payload”, J. of Guidance, Control, and Dynamics, vol.26, No. 5, 794-804 (Sept.–Oct. 2003).

Pedreiro, N., M. Gonzales, B. Foster, T. Trankle, and D. Roth, “Agile Disturbance Free Payload”, AIAA Guidance, Navigation, and Control Conference (2005), paper #AIAA-2005-5876, (2005).

Saulson, P.R., “Thermal noise in mechanical experiments”, Phys. Rev. D 42, 2437–2445 (1990)

Stebbins, R.T., P.L. Bender, J. Hanson, C.D. Hoyle, B.L. Schumaker, and S Vitale, “Current error estimates for LISA spurious accelerations,” Class. Quantum Grav. 21 S653 (2004).

Trankle, T., N. Pedreiro, and G. Andersen, “Disturbance Free Payload Flight System Analysis and Simulation Methods”, AIAA Guidance, Navigation, and Control Conference (2004), paper # AIAA-2005-5875, (2005).

Contact information:

Dr. Michael Shao
Staff scientist, Science Division,
Jet Propulsion Laboratory, MS 321-522
4800 Oak Grove Drive, Pasadena, CA 91109
Phone: (818) 393-2600
Email: michael.shao@jpl.nasa.gov

Supplemental information:

- Category of response:
  - ***Instrument concept***: the new concept is based on the novel Disturbance Free Payload architecture and torsion balance as a test mass
    Brief description: Our concept uses torsion balances as the test mass, cold gas thrusters,
    Enabling technologies:
    Brief description: Our concept is based novel spacecraft architecture, known as Disturbance–Free Payload that reduces requirements on key mission instruments.
- Answer to these questions:
  - We will be willing to participate and present our concept at the workshop, if invited. **Yes**
  - Does your organization have any sensitive or controlled information (e.g., export controlled, proprietary, competition sensitive) that might be useful for this exercise? **Yes**. If so, are you willing to discuss this information with NASA if proper arrangements can be made to protect the information? **Yes**.