Laser Interferometer Space Antenna (LISA)

Astro2010 RFI #2 Space Response

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1. Executive Summary and Science Overview

1.1. Executive Summary

Gravitational waves are time-varying perturbations of the structure of space-time itself. They are generated by the rapid accelerated motions of very compact objects, such as black holes of all sizes, neutron stars and white dwarfs. These waves carry unique and detailed information about extreme interactions central to the origin and evolution of stars, galaxies, and the Universe. They have been confirmed indirectly by observations of binary pulsars, and they are likely to be detected directly within the next decade by the large ground-based instruments operating in the 10-1000 Hz range, such as LIGO and Virgo, which currently have sensitivities sufficient for rare events, and which are upgrading to sensitivities at which detections should be commonplace.

The Laser Interferometer Space Antenna (LISA) is a joint NASA–ESA project to develop and operate a space-based gravitational-wave detector sensitive between 3×10^{-5} and 0.1 Hz. This frequency range is expected to have the largest number of, the greatest variety of, and the strongest gravitational-wave sources - a rich trove of astrophysical information that is only accessible with observations from space. LISA works by measuring changes in the separation between free-flying, fiducial ("proof") masses housed in three identical spacecraft five million kilometers apart. The spacecraft move in Earth-like solar orbits (20° behind Earth), chosen to maintain the constellation in a quasi-equilateral triangle throughout the mission. Each spacecraft hosts two identical sets of interferometers and two proof masses; laser interferometry is used, in a manner similar to spacecraft radar tracking, to measure separation changes along each side of the triangle. There is only one science-operation mode for the entire constellation, with no re-orientations, no maneuvers, no orbital maintenance, and modest data rates.

The LISA measurement concept relies on laser metrology and "drag-free" flight. Laser metrology is routinely performed in the laboratory at levels exceeding LISA's requirements by orders of magnitude; drag-free flight has been an established space technology for more than three decades, but LISA requires better performance.

LISA Pathfinder (LPF) is an ESA-led technology demonstration mission for LISA scheduled for launch in 2011. LPF will test proof masses (with supporting subsystems), drag-free control, microthrusters and interferometry technology. The Pathfinder ground-development program is now complete; engineering models of the science instruments have been built and flight qualified. Flight hardware is under construction. Thus, much of the LISA technology risk has already been retired by the development of LISA Pathfinder. The remaining benefits will be in hand before the end of LISA's Phase A.

The *Science Overview* section that follows describes how LISA's rich and diverse scientific objectives are rigorously connected to science requirements through carefully defined science investigations and associated observations. The result is a robust and stable set of science requirements that are essentially characterized by four critical parameters: the arm length, the optical measurement sensitivity, the residual acceleration noise on the proof masses, and the mission duration. These performance requirements have been flowed down to the instrument subsystem levels, in some cases even lower. The LISA science return can be estimated for both nominal and alternate values of these parameters, as discussed in the responses to the questions below.

The LISA concept has been stable since 1997, and the architecture has been specified in detail and analyzed to a high degree. The *Technical Implementation* section describes the two instrument subsystems, the Interferometry Measurement System (IMS) and the Disturbance

Reduction System (DRS). The IMS measures changes in the separation of the proof masses, and provides information for spacecraft, proof mass and telescope control. The DRS isolates the proof mass from disturbances that might mask gravitational waves, and controls spacecraft position and attitude. Mission design calls for a single launch, followed by cruise trajectories to the final operational orbits. The LISA spacecraft bus is a simple vehicle based on mature technologies, except for its micronewton thrusters. Two different thruster technologies have been developed, and will be tested on Pathfinder.

Much of the risk of LISA's enabling technologies has already been retired, either in the Pathfinder program, or by more conventional ground-based development. As described in the responses to technology questions in the *Payload* and *Spacecraft* subsections and in the *Enabling Technology* section, two of the three enabling technologies will be at Technology Readiness Level (TRL) 7 by the start of Phase B, and the other at TRL 6.

Mission Operations Development describes LISA's four phases and its modest science operations needs: single mode, low data rate, no maneuvers, contacts every other day, limited planning. A Missions Operations Center will forward science data and science housekeeping data to NASA and ESA Science Operations Centers (SOCs). The analysis required to produce the final data products is non-trivial, but many of the algorithms have already been demonstrated in mock data exercises. The complete archive of final and intermediate data products will be less than a terabyte. The NASA SOC will manage a guest investigator program.

The *Programmatics & Schedule* section documents the established NASA–ESA partnership for LISA, which has already been operating effectively for eight years. The detailed schedule, which underlies the coordinated NASA and ESA cost estimates, relies on a partial parallel-build of identical copies of science instrumentation, spacecraft bus, and propulsion modules needed on each spacecraft.

The *Cost* section describes the process by which the three requested cost scenarios were derived from the Project's grass-roots cost estimate. It also describes a recent independent cost and schedule estimate by Aerospace Corporation that agrees with the Project estimates for both cost and schedule within 5%.

Finally, LISA's evolution since the last decadal (AANM) and BEPAC are described in *Changes Since Previous NRC Reviews*. The mission concept and architecture are largely unchanged since before AANM. The cost estimate used by AANM was unreliable, and not comparable to any costing done since. The cost estimate done by the BEPAC was an outlier with respect to two other independent LISA cost estimates. After BEPAC the Project redid its cost estimate by grass-roots rather than parametric methods, and the cost estimate is essentially unchanged.

1.2. Science Overview

In this section we discuss the LISA science objectives and how these lead to measurement performance requirements. The LISA Project has a well-defined scheme for this flow-down. For each *science objective*, a set of *science investigations* is defined which lead directly to *observation requirements*. The latter are given in terms of observable quantities, such as the number and type of GW sources that must be observed together with the required precision of parameter estimates (e.g., of mass, spin, luminosity distance, etc.). The ensemble of *observation requirements* is then used to calculate overall *science requirements* in terms of strain sensitivity, observation time, latency, etc. These *science requirements* can be further broken down into detailed *measurement requirements*. In summary, the LISA flow-down is: *science objectives* →

science investigations → *observation requirements* → overall *science requirements* → *measurement requirements*. A more complete description of the science and flow-down process is given in references [O-2, O-7, O-8].

Space does not permit us to give the complete table of objectives and investigations. An example is given in Table 1-1, which lists the scientific investigations that correspond to two science objectives. The full table is in Appendix A. Detailed motivations for the objectives and investigations are given in [O-2 and O-7]; here we briefly summarize LISA's primary sources and estimated event rates:

Massive black hole binaries – Mergers of binaries involving two black holes with mass M in the range $10^4 M_\odot < M < 10^7 M_\odot$, as far away as z ~ 30. Estimates suggest that LISA will see tens to hundreds of MBH mergers per year.

- **Intermediate-mass black holes** – Mergers of binaries involving at least one black hole with mass $10^2 M_\odot < M < 10^4 M_\odot$. LISA can detect these events out to z ~ 20.
- **Extreme-mass ratio inspirals** – Stellar-mass compact objects (i.e., black holes, neutron stars, and white dwarfs) with M ~ 1-10 $M_\odot$ in capture orbits around massive black holes in galactic nuclei. LISA can detect these events and extract extremely accurate parameters out to z ~ 1. The best estimate of the detection rate is ~ 50/yr, but could be substantially higher or lower.
- **Close binaries of stellar-mass compact objects** – Close binary systems of stellar-mass black holes, neutron stars, and white dwarfs in the Milky Way, with orbital periods between 100 and 10,000 s. LISA will easily detect several thousand of the brightest sources. The remainder will constitute a diffuse foreground signal between 0.2 and 2 mHz.

LISA might also detect signals from cosmological backgrounds (e.g., from an early-Universe phase transition), bursts from cusps on cosmic (super-)strings, and unforeseen sources.

Table 1-1. Examples of LISA science objectives and supporting science investigations.

Science Objectives	Science Investigations
Trace the growth and merger history of massive black holes and their host galaxies	• Determine the relative importance of different black hole growth mechanisms as a function of redshift. • Determine the merger history of 1×10^4 to $3\times10^5 M_\odot$ black holes before the era of the earliest known quasars ($z \sim 6$). • Determine the merger history of 3×10^5 to $1\times10^7 M_\odot$ black holes at later epochs ($z < 6$).
Explore stellar populations and dynamics in galactic nuclei	• Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals. • Study intermediate-mass black holes from their capture signals. • Improve our understanding of stars and gas in the vicinity of Galactic black holes using coordinated gravitational and electromagnetic observations.

1. Describe the measurements required to fulfill the scientific objectives expected to be achieved by your activity.

LISA fulfills its scientific objectives by observing the time-varying strain in space-time caused by gravitational wave emission from distant sources. This strain can be determined by measuring the changing separation between fiducial reference objects, called "proof masses".

These proof masses must be isolated from external forces and disturbances that will appear as noise in the measurement of the gravitational wave strain. All LISA science objectives can be fulfilled by measuring the change in the separation of proof masses over three 5-million kilometer baselines within a frequency band from $3\text{x}10^{-5}$ to 0.1 Hz during a 5-year period and to an accuracy of 10 pm.

2. Describe the technical implementation you have selected, and how it performs the required measurements.

The LISA concept uses continuous laser ranging of a 5-million kilometer separation between free-falling proof masses in very low disturbance environments. The laser ranging monitors the change in phase of a distant laser relative to an on-board reference laser. The sources in LISA's frequency band require strain sensitivity as low as $10^{-20}/\sqrt{}$ Hz. That strain sensitivity is achieved by interferometric readout to $\sim 10^{-5}$ cycles/$\sqrt{}$ Hz of 1 micron light over the 5 million km arm length. Most of the GW signals can be coherently integrated for months to years. The LISA Interferometry Measurement System (IMS) is characterized by its displacement sensitivity. Disturbances on the proof masses are kept low by a benign space environment, "drag-free" operation and careful design of payload and spacecraft. A "drag-free" spacecraft encloses a free-falling proof mass, senses its position, and keeps the spacecraft centered on the proof mass. This technology reduces the time-varying forces on the proof mass from the external environment and the surrounding spacecraft equipment. In LISA, isolation of the proof mass from disturbances is accomplished by the Disturbance Reduction System (DRS), characterized by the level of residual acceleration noise on the proof masses. For further technical-implementation details see [O-1].

3. Of the required measurements, which are the most demanding? Why?

The most demanding aspect of the required measurements is reduction of acceleration noise on the proof masses. Reduction of acceleration noise is demanding because the required levels of reduction are a few orders of magnitude below what has been previously demonstrated on spacecraft. Control of acceleration noise requires several technologies including micronewton thrusters and capacitive sensing and control of the proof mass, as well as careful design of the payload and spacecraft bus. These technologies will be demonstrated on LISA Pathfinder during Phase A of the LISA mission. See [O-13] for additional details.

4. Present the performance requirements (e.g. spatial and spectral resolution, sensitivity, timing accuracy) and their relation to the science measurements.

The principal science performance requirement, defined from $3\text{x}10^{-5}$ to 0.1 Hz, is the LISA strain sensitivity curve (red) shown in Figure 1-1. That instrumental noise curve is compared against the strength of some representative LISA sources: some known compact white dwarf binaries (aka 'verification binaries'), an Extreme Mass Ratio Inspiral (EMRI), and two massive black MBH merger events. The blue curve shows the confusion-noise background from unresolved Galactic binaries, while the dotted black curve shows the sensitivity level to be demonstrated by LISA Pathfinder performance.

The analytic form of the strain sensitivity curve in Figure 1-1 is given in Table A-2 in Appendix A. The strain sensitivity, $\sqrt{S_h(f)}$, is determined by two noise contributions and two parameters. The noise contributions are the displacement noise of the IMS, which dominates above about 4 mHz, and the residual acceleration noise from the DRS, which dominates at lower frequencies. The two parameters are the measured armlength of the interferometer ($5\text{x}10^{6}$ km) and the duration of science observations (5 years). At high frequencies the sensitivity curve rises, because the wavelength of the gravitational waves becomes shorter than the armlength. Table A-2 gives the values of the allocated noise contributions and shows how they combine to give the strain sensitivity curve in Figure 1-1.

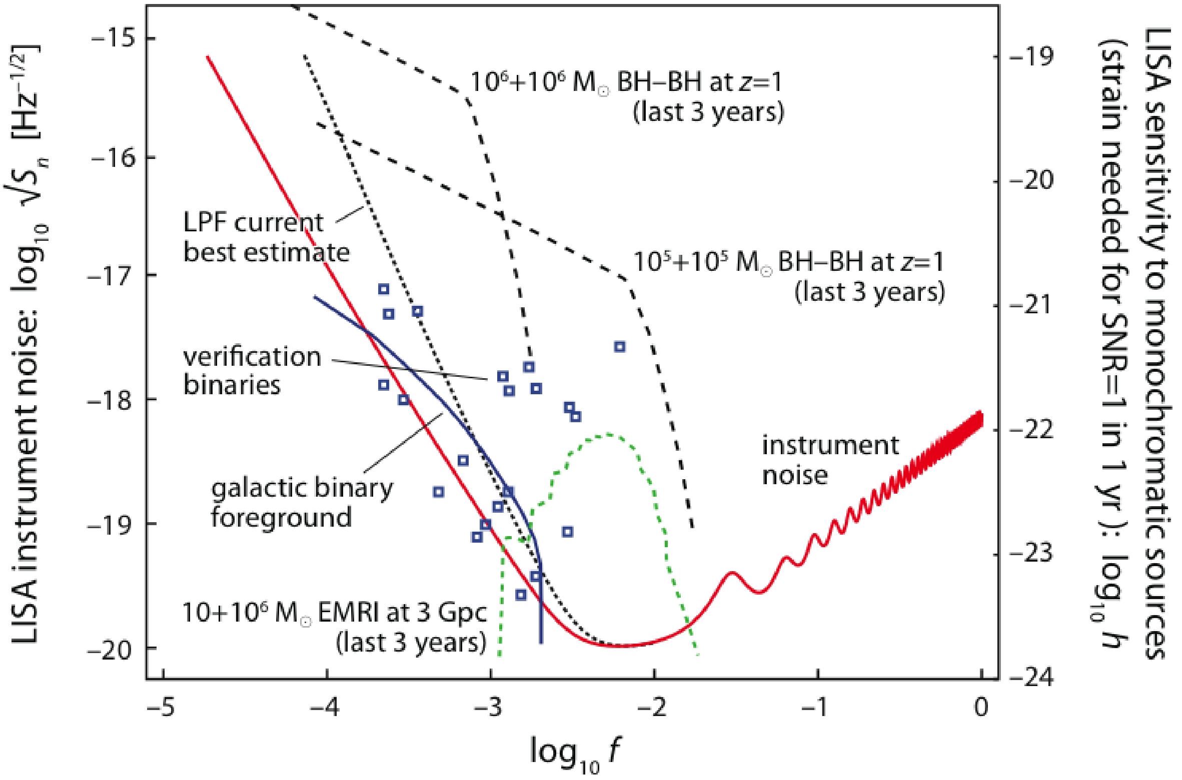


Figure 1-1. LISA Sensitivity. Sources above the red and blue lines are detectable by LISA. The height of sources above the noise approximates their matched filtering signal-to-noise ratio (SNR) in a one-year integration; the corresponding strain is shown on the left vertical axis. See [O-7] and the text for additional details.

5. Present a brief flow down of science goals/requirements and explain why each payload instrument and the associated instrument performance are required.

The strain sensitivity requirement, shown in Figure 1-1, is flowed down to a top-level displacement noise allocation (18x10^{-12} m/√Hz) for the Interferometry Measurement System and a top-level residual acceleration noise allocation (30x10^{-16} m/s^2/√Hz) for the Disturbance Reduction System, as shown in Table A-2. Then, those noise allocations are each sub-allocated, first to a system margin, and then to contributing effects in each of those instrument subsystems. Summaries of the sub-allocations are given Tables A-3 and A-4 in Appendix A. A more extensive description of the error budget can be found in reference [O-8].

6. For each performance requirement, present as quantitatively as possible the sensitivity of your science goals to achieving the requirement. For example, if you fail to meet a key requirement, what will the impact be on achievement of your science objectives?

We consider three scenarios for the impact of degraded performance on the science objectives:

- **LISA's low-frequency sensitivity is only at the level that one could safely predict based on LISA Pathfinder performance** (dotted black curve in Figure 1-1). This degradation would decrease the number of detectable binaries at $f < 0.7\ mHz$, and hence also eliminate a few "verification" binaries. However the main effect would be to substantially decrease LISA's angular resolution for MBH mergers. That is because angular resolution improves substantially with the length of time that the MBH binary is detectable (i.e., lies above the noise curve). This degradation would substantially worsen our chance of finding EM counterparts to MBH mergers, and hence of getting the source redshift and doing high-precision cosmology. Most other science is retained.

- **LISA's sensitivity is degraded by a factor of 3 at all frequencies.** (There is no physical reason for an overall degradation; this is a "strawman" scenario.) The biggest effect would be on EMRI science, since the expected rate would decrease from ~50/yr to ~2/yr, which could mean no detections given the uncertainty in EMRI rates. Detections of MBHs would be reduced by a factor ~2 and detections of galactic WD binaries would be reduced by a factor ~10, but it is clear that a large fraction of the science from both these source types would be retained.
- **Loss of one gravitational reference sensor (GRS),** which entails loss of two laser links, rendering LISA the equivalent of a single Michelson interferometer. It is actually not a science requirement that LISA maintain 6 working links throughout the mission, but it is important to consider how the science would degrade when/if a GRS is lost. Detection rates for the different source types would decrease by factors of only ~1.5–3. The largest impact would be degraded angular resolution for MBH mergers; the number of sources that LISA could localize to within 10 sq. degrees (the LSST field-of-view) would decrease, significantly reducing the chance of finding an EM counterpart. In addition, LISA's capability for detecting an isotropic diffuse background is degraded. Thus LISA science is fairly robust against the loss of one GRS.

2. Technical Implementation

The constellation is the single LISA science instrument. The usual vocabulary of ‘instrument,’ ‘payload,’ ‘spacecraft’ and ‘observatory’ does not fit the LISA architecture. We use ‘payload’ to describe that *part* of the science instrument on a single vehicle, ‘sciencecraft’ to describe the payload plus spacecraft bus, and ‘constellation’ to describe the three sciencecraft. The standard tables in this section have been adapted to the LISA architecture.

2.1. Payload Instrumentation

1. Describe the proposed science instrumentation, and briefly state the rationale for its selection. Discuss the specifics of each instrument (Inst #1, Inst #2 etc) and how the instruments are used together.

The LISA concept for directly detecting the oscillating strain in spacetime caused by gravitational waves underlies all laser interferometer-based gravitational wave detectors and was suggested by Bondi [S-1]. A gravitational wave is detected by measuring the time-varying changes of distances between free-falling mirrors. The key ingredients are undisturbed proof masses and the interferometry system to measure distance changes between them. A space-based detector benefits from accumulating the strain over very long baselines that magnify the distance changes.

Each sciencecraft contains a Disturbance Reduction System (DRS) comprising two Gravitational Reference Sensors (GRSs), each with a proof mass [O-1], with performance defined by the residual acceleration. In addition, each sciencecraft contains two transmit/receive terminals of the Interferometry Measurement System (IMS), each constituting one end of a measured path and characterized by the displacement sensitivity. Amplitude spectral densities, the square root of the power spectral density, most naturally describe time-variable quantities, since LISA is an amplitude detector, not a power detector like electromagnetic devices.

The DRS and GRS were selected for low residual acceleration noise and the long flight heritage of drag-free satellites and flight accelerometers. The IMS design was selected for high displacement sensitivity with modest laser power and telescope size, and relative ease of the phase measurement) [O-5].

2. Indicate the technical maturity level of the major elements and the specific instrument TRL of the proposed instrumentation (for each specific Inst #1, Inst#2 etc), along with the rationale for the assessment (i.e. examples of flight heritage, existence of breadboards, prototypes, mass and power comparisons to existing units, etc). For any instrument rated at a Technology Readiness Level (TRL) of 5 or less, please describe the rationale for the TRL rating, including the description of analysis or hardware development activities to date, and its associated technology maturation plan.

Questions 2, 7, and 13 each deal with various aspects of technology development. Table 2-1 provides TRL assessments by the Project and by Aerospace Corporation in a recent independent review. Since LISA Pathfinder is such an extraordinary component of LISA technology development, TRLs at the start of Phase B are also given to anticipate the progress from LPF and the on-going ground-based technology development program.

Table 2-1. Technical Maturity Levels of Major Elements and Instrumentation

Technology	Function	Current TRL		Phase B Start TRL		Rationale for TRL	Flight Heritage, Existing Hardware, and Maturation Plan
		NASA	Aerospace	NASA	Aerospace		
Gravitational Reference Sensor (GRS)	Inertial reference points for strain measurements	5-6	4-5	7	7	LPF GRS development & tests	Heritage from LPF. LPF will bring LISA GRS to flight readiness and validate noise model.
Optical Assembly Pointing Mechanism (OATM)	Keep far SC in FOV of telescope	6	3	6	4-5	• Flight-qualified actuators meet requirements (e.g. PI's *Nexline*) • Aerospace was not aware of existing documentation.	ESA/NASA to develop independent mechanical designs using flight-qualified actuators.
Point Ahead Actuator Mechanism (PAAM)	Compensate for apparent motion of distant SC	3-4	4-5	6	4-5	• Laboratory demonstration of actuator prototype (TNO). • Aerospace was not aware of existing documentation.	Continue actuator testing with TNO and RUAG/CSEM designs.
Laser subsystem	Light source for interferometry	4-6	4-6	6	6	LPF laser (Tesat) meets seed laser requirements.	Heritage from LPF, TerraSarX, & N-FIRE. Integration into TRL 6 laser system expected by 2010.
Laser Frequency Noise Mitigation	Reduce laser frequency noise in science signal	4-5	4	6	5	Laboratory demonstrations, simulations, & detailed noise models.	Refine design, identify components, & construct breadboards for laboratory testing.
Optical Bench	Interfere beams	5-6	4	6	6	The LPF EM meets LISA requirements.	Construction heritage from GP-B & LPF. Ground development.
Telescope	Transmit/Receive Beams	5-6	4-6	6	6	Standard optical design w/ moderate requirements. Similar to SILEX, Herschel, Aladin, Akari, STSS, & SCATS	Laboratory tests of scale models, simulations of wavefront propagation.
Phase Measurement System (PMS)	Extract position/angle information	4-5	5	6	6	TRL 4 PMS demonstrated LISA performance. Similar to Blackjack GPS receiver.	TRL 5 expected late 2009, TRL 6 expected end of 2010.

3. In the area of instrumentation, what are the three primary technical issues or risks?

Table 2-2. Primary Instrumentation Risks

Risk	Mitigation
Failure of a single GRS system degrades science performance.	▪ System is single-point failure tolerant by design. ▪ Direct flight heritage: LPF will fly the LISA GRS. ▪ Most science goals can be achieved with up to two GRS failures.
GRS performance falls short of the performance expected from Pathfinder demonstration, degrading science performance.	▪ LISA GRS performance at the LPF limit affects mainly the accuracy of LISA's angular resolution for Massive Binary Black Hole mergers. ▪ Extensive ground testing includes exaggerated disturbance testing to fully characterize noise sources.
Laser frequency noise suppression is inadequate, degrading science performance.	▪ Three level suppression system currently planned. ▪ Laboratory measurements demonstrate performance. ▪ Full system level demonstration planned for ground testing.

4. Fill in entries in the Instrument Table. Provide a separate table for each Instrument (Inst #1, Inst #2 etc). As an example, a telescope could have four instruments that comprise a payload: a telescope assembly, a NIR instrument, a spectrometer and a visible instrument each having their own focal plane arrays.

Table 2-4 describes the key performance parameters and distinguishing characteristics of the LISA scientific instrument, which is the entire constellation of three sciencecraft. The table has been modified to better fit the LISA architecture and is organized by constellation, Interferometry Measurement System, and Disturbance Reduction System.

5. If you have allocated contingency please include as indicated along with the rationale for the number chosen. If contingency is unknown, use 30% contingency.

Contingency in payload mass and power are shown in Table 2-5. Contingency in science performance is contained in two places. The amplitude spectral density allocations for displacement noise and acceleration noise both include 30% contingency over the current best estimate (CBE) [see Tables A-3 and A-4]. In addition, most of the science requirements are written assuming that only four of the six links are working (see response to Q6 in Section 1).

6. Fill in the Payload table. All of the detailed instrument mass and power entries should be summarized and indicated as Total Payload Mass and Power as shown in the table.

Table 2-5 shows total payload mass and average power in science mode with contingencies.

7. Provide for each instrument what organization is responsible for the instrument and details of their past experience with similar instruments.

The "2004 Agreement" between ESA and NASA established an allocation of roles and responsibilities (See answer to Q1 in Programmatics and Schedule). The ESA portion of the payload, called the LISA Opto-mechanical Core System (LOCS), includes the Gravitational Reference Sensor (GRS), the optical bench, the laser subsystem, and the laser stabilization subsystem, and is based in large part on the LPF experience [O-4, O-13]. LISA is already benefiting from this experience.

The NASA portion, called the LISA Instrument Metrology and Avionics System (LIMAS), comprises the frequency distribution system, the phase measurement subsystem and a metrology processor, and is based on NASA experience with the Blackjack GPS receiver used on GRACE and ICESat. The 2004 Agreement anticipates a final allocation of roles and responsibilities before the Implementation Phase. To ensure real choices for that final allocation, both agencies are developing some subsystems.

8. For the science instrumentation, describe any concept, feasibility, or definition studies already performed (to respond you may provide copies of concept study reports, technology implementation plans, etc).

Extensive documentation is available. Page limits force us to put a representative list in Appendix B. The list has been annotated to facilitate its assessment.

9. For instrument operations, provide a functional description of operational modes, and ground and on-orbit calibration schemes. This can be documented in Mission and Operations Section. Describe the level of complexity associated with analyzing the data to achieve the scientific objectives of the investigation. Describe the types of data (e.g. bits, images) and provide an estimate of the total data volume returned.

LISA science operations have a single simple operating mode where data are collected and buffered for transmission to the ground. The sciencecraft follow passive Kelperian orbits (no station keeping), attitude control is maintained by the DRS, and there are no maneuvers. All sources are simultaneously observed all of the time [S-9], with scheduled interruptions only for short periods of time needed for maintenance tasks.

As with all interferometers, no calibration is needed for the main displacement measurement. Spacecraft control system parameters and housekeeping instruments that need calibration require only conventional schemes and method, with no unusual requirements.

The primary data are time series representing the phase variation of the signals from interferometers on the optical bench supplemented by time series of various “housekeeping” signals on the sciencecraft. No onboard data processing is conducted. See Table 4-1 in the Mission Operations section for a description of the data stream and communications.

Ground processing and data analysis extract an absolute change in distance between proof masses and science signals and parameter estimates for astrophysical sources [O-9]. Total daily average data volume is 1.3 GB with a total volume over a 5 year mission of 2.4 TB [O-9].

A description of the mission timeline is provided in Q1 of the Mission Operations section. Additional details are contained in the formulation documents [E-1-4, P-2, S-4].

10. Describe the instrument flight software, including an estimate of the number of lines of code.

Due to the integrated nature of the LISA spacecraft bus and payload, most of the flight software is part of the bus. For example, the drag-free control system, which resides in the bus, uses the output of the gravitational reference sensor and phase measurement system to provide the control required for the science measurement. However, the majority of the software for performing the interferometric measurement is resident in the payload.

The Instrument Processing Unit (IPU) within the phase measurement system contains a dedicated processor for back-end phasemeter processing, signal routing and simple communication interactions with the spacecraft. The software has only two modes, its standard autonomous tracking of laser interferometer heterodyne signals and a sequence driven mode during initial constellation acquisition. At power-up the IPU will boot and automatically start tracking any signals present. Data packets are pushed out to the spacecraft on two serial channels, one including one packet at 0.1 Hz containing the science data stream and telemetry (sampled at 3.3 Hz) to be stored for forwarding to ground, and a 10 Hz output packet for use with the drag-free control system. During acquisition mode the system will execute a series of laser frequency sweeps and signal tracking upon command from the spacecraft. The IPU software is derived from the BlackJack receiver code flown on GRACE, with an estimated 31,000 lines of code. Commanding and software uploads will follow the BlackJack Data Link Protocol, JPL-D-20675, which has been used successfully on over a dozen spacecraft.

11. Describe any instrumentation or science implementation that requires non US participation for mission success.

Under the 2004 Agreement, several mission critical subsystems in the payload are assigned to ESA (see answer to Question #7 in this subsection). NASA could provide all but the GRS, which would require a major development effort to reproduce ESA's accomplishments for LISA Pathfinder.

12. Please provide a detailed Master Equipment List (MEL) for the payload sub-categorized by each specific instrument indicating mass and power of each component. This table will not be counted in the page totals.

Table 2-3 shows a Master Equipment List for the LISA payload for each of three identical sciencecraft.

13. Describe the flight heritage of the instruments and its subsystems. Indicate items that are to be developed, as well as any existing hardware or design/flight heritage. Discuss the steps needed for space qualification.

Table 2-1 shows the design experience or flight heritage and development status of the LISA instrument subsystems. Many of these subsystems already benefit directly, or indirectly, from the LISA Pathfinder development. For the GRS, the benefit is direct flight heritage because the LPF GRS is the LISA GRS. For other subsystems the design, construction, and test/validation is similar if not the same. Reference [P-4] lays out a detailed technology development plan.

Table 2-3. Payload Master Equipment List (One of Three Identical Sciencecraft)

Name	Flt Qty	Unit Mass CBE (kg)	CBE Total (kg)	Total Mass incl. 30% Cont. (kg)	Science Mode On Qty	Unit Power CBE (W)	CBE Total (W)	Total Power incl. 30% Cont. (W)
GRS								
Gravitational Reference Sensor	2	12.80	25.6	33.3	2	17.3	34.6	45.0
Charge Management Unit	1	5.10	5.1	6.6	1	11.8	11.8	15.3
Caging System Electronics	1	5.89	5.9	7.7	1	0.0	0.0	0.0
Diagnostic Driver Electronics	1	1.50	1.5	2.0	1	12.0	12.0	15.6
Laser								
Laser Units	4	7.00	28.0	36.4	2	50.0	100.0	130.0
Optical Assembly								
Optical Bench	2	5.60	11.2	14.6	2	0.0	0.0	0.0
Optical Assembly Electronics	1	2.70	2.7	3.5	1	32.0	32.0	41.6
Point Ahead Actuator	2	2.00	4.0	5.2	2	0.0	0.0	0.0
Fiber Positioner	2	1.00	2.0	2.6	2	0.0	0.0	0.0
OA Structure	2	5.00	10.0	13.0	2	0.0	0.0	0.0
Telescope	2	6.50	13.0	16.9	2	0.0	0.0	0.0
Telescope Shield Structure	1	6.00	6.0	7.8	1	0.0	0.0	0.0
Focus Mechanism	2	0.25	0.5	0.7	2	0.0	0.0	0.0
Optical Assembly Tracking Mechanism	2	1.00	2.0	2.6	2	0.0	0.0	0.0
Optical Assembly Mechanism Electronics	1	3.50	3.5	4.6	1	5.0	5.0	6.5
LIMAS								
Phase Measurement System	1	15.00	15.0	19.5	1	54.3	54.3	70.6
Ultra-Stable Oscillator (USO)	2	0.50	1.0	1.3	1	3.0	3.0	3.9
Thermal								
Heaters, Survival	1	1.50	1.5	2.0	1	0.0	0.0	0.0
Total			138.5	180.0			252.7	328.5

Table 2-4. Key Performance Parameters and Distinguishing Characteristics of the LISA Scientific Instrument (The Constellation of Three Sciencecraft)

Constellation	**Value/Description**	**Units**
Number of sciencecraft	3	each
Separation between spacecraft	5×10^9 +/- 1%	meters
Measurement bandwidth	3×10^{-5} to 10^{-1}	Hz
Length of science operations	5	years
Average science data rate per S/C to be sent to ground	0.87	kbps
Interferometer Measurement System	**Value/Description**	**Units**
Displacement noise amplitude spectral density (allocation)	18×10^{-12}	m/√Hz
Laser type	Nd:YAG master oscillator, Yb doped fiber amplifier	
Laser wavelength	1.064	μm
Transmitted Laser Power, end of life	0.7	W
Telescope Diameter	0.40	m
Disturbance Reduction System	**Value/Description**	**Units**
Acceleration noise amplitude spectral density (allocation)	30×10^{-16}	$m/s^2/\sqrt{Hz}$
Number of proof masses per sciencecraft	2	each
Shape and size of proof mass	Cube, 46	mm
Gap between proof mass and housing in measurement direction	4	mm
Drag-free performance in measurement direction (allocation)	5	nm/√Hz

Table 2-5. Payload Mass and Power (For Single Sciencecraft)

Item	**Current Best Estimate (CBE)**	**Percent Contingency**	**CBE Plus Contingency**	**Units**
Payload mass	138	30%	180	kg
Average payload power	252	30%	328	W

2.2. Mission Design

1. Provide a brief descriptive overview of the mission design (launch, launch vehicle, orbit, pointing strategy) and how it achieves the science requirements (e.g. if you need to cover the entire sky, how is it achieved?).

All three spacecraft are launched in a single integrated stack on a medium-class EELV. After the initial launch, the spacecraft separate and enter a 14 month cruise phase during which the propulsion modules perform three deterministic transfer maneuvers to inject each spacecraft into the appropriate solar orbit (Table 2-7a). Final delivery of each sciencecraft on station is marked by separation from the propulsion module, and commissioning begins as described in the Mission Operations development section (Q1). The science operations phase begins upon completion of commissioning activities and data collection follows until the end of mission. These phases are described in detail in the Mission Operations section and references [S-5, S-6, O-10].

The chosen orbits do not require station-keeping to preserve a near-equilateral triangular formation with separations +/- 1% for the 5 year mission duration [O-17]. The entire sky is observed in both polarizations of gravitational radiation naturally as the quadrupolar sensitivity pattern of the instrument sweeps across the sky in the normal course of the orbits. The resulting AM and FM modulations of the signals are used to extract the angular position of the sources.

2. Describe all mission software development, ground station development and any science development required during Phases B and C/D.

During Phase B mission operations software will be system engineered with updates and modifications planned and costed. During Phase C the baseline capabilities will be modified to support the critical path for downlink and uplink in ATLO. During Phase D all remaining modifications to software necessary to support operations will be completed. The LISA project will benefit from a large inheritance of existing multi-mission operations code base. The amount of modification to inherited mission operations software necessary to support the LISA mission is less than 1% of the existing code base with one exception: the downlink telemetry decommutation and Level 0 science product builder, which will require approximately 10-20% modification to the existing code base.

No ground station development is required to support the LISA mission. All necessary hardware will be available in the DSN by 2015.

In Phases C/D, science development will be led by the LISA Science Center. During Phase C, the Center will develop data analysis software, based on algorithms and prototype code already validated by members of the LISA Science Team and their research groups. The Center will support this work by developing and maintaining common software tools and libraries. The activity will benefit from the experience gained in the Mock LISA Data Challenge program [O-15], begun in 2005, which has already demonstrated proof-of-concept algorithms for most of the LISA science objectives, and which maintains its own open-source library of data-analysis and data-management [O-18].

In Phase D, the Center will design and implement a production data-analysis system, including a centralized computing resource. It will perform science analyses to generate Level-3 data products such as source catalogs, "source-cleaned" data streams, and event alerts. In addition, the Center will develop the LISA Science Data Archive and provide the capability of querying astronomical databases for candidate objects associated with GW events.

3. Provide entries in the mission design table. For mass and power, provide contingency if it has been allocated. If not, use 30% contingency. To calculate margin, take the difference between the maximum possible value (e.g. launch vehicle capability) and the maximum expected value (CBE plus contingency).

See Tables 2-7a, b and c. The tables have been modified to accommodate the LISA constellation of three identical sciencecraft in similar heliocentric orbits with three identical propulsion modules.

4. Provide diagrams or drawings showing the observatory (payload and s/c) with the instruments and other components labeled and a descriptive caption. Provide a diagram of the observatory in the launch vehicle fairing indicating clearance.

See Figure 2-1.

5. For the mission, what are the three primary risks?

Table 2-6. Primary Mission Risks

Risk	Mitigation
Acquisition of the optical links through the telescopes between spacecraft	▪ Development of multiple acquisition techniques ▪ Thorough analysis and verification of the selected acquisition techniques ▪ Ground testing, with hardware in the loop, of the selected acquisition techniques
Transfer Burns fail to insert spacecraft into final orbits	▪ Appropriate redundancy in the Propulsion Module propulsion system design ▪ Additional testing of propulsion system components if required ▪ Adequate delta-v/propellant margins to account for off-nominal performance
PM Separation results in high spacecraft rotation rate	▪ Selection of high reliability hardware ▪ Detailed separation analyses, incorporating hardware test results in final form ▪ Adequate propellant margins ▪ Battery sizing to worst case tip-off rates and ACS recovery time

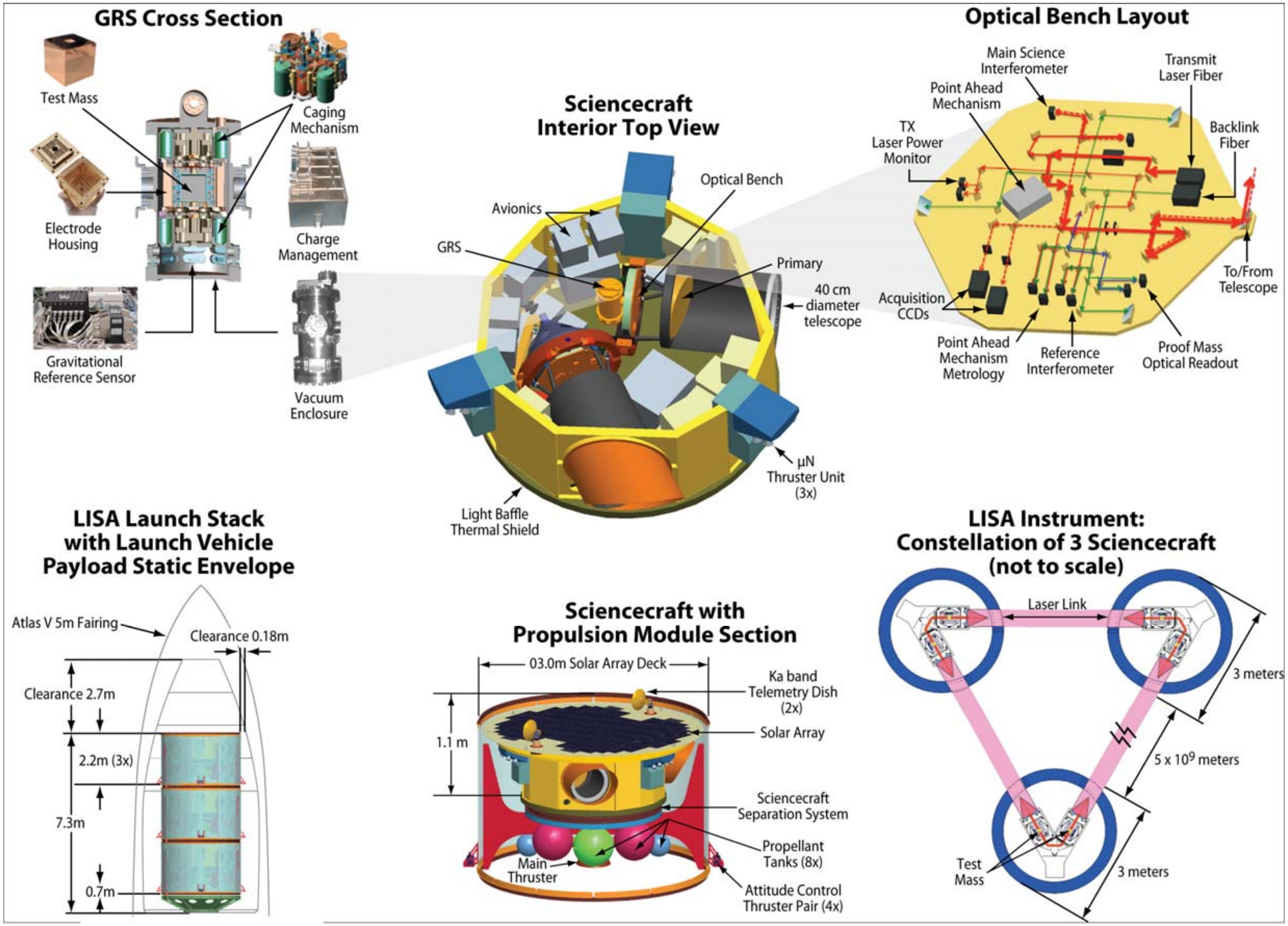


Figure 2-1. LISA Observatory Showing Launch Stack, Propulsion Module, Sciencecraft

Table 2-7a. Mission Design - Orbits

Mission Design				
Orbit Parameters	**EME 2000 Coordinate System**	**Sciencecraft #1**	**Sciencecraft #2**	**Sciencecraft #3**
	Semi-Major Axis	1 AU (149x10^6 km)	1 AU (149x10^6 km)	1 AU (149x10^6 km)
	Eccentricity	0.018	0.0095	0.0089
	Inclination	0.89 deg	0.99 deg	0.99 deg
	Argument of Perihelion	90.60 deg	32.52 deg	148.24 deg
	Longitude of Ascending Node	3.65 deg	126.76 deg	240.29 deg
	Mean Anomaly	343.95 deg	278.42 deg	51.02 deg
Mission Lifetime	6.5 years (1 mo. launch, 14 mo. cruise, 3 mo. commissioning, 60 mo. science), 10 year goal			
Maximum Eclipse Period	Heliocentric orbits do not have eclipses.			

Table 2-7b. Mission Design - Mass

Mass			
System	**CBE Mass (kg)**	**Contingency (%)**	**Mass with Contingency (kg)**
Spacecraft Bus Total	348	30%	452
Payload Total	138	30%	180
Propulsion Module Dry Total	314	30%	409
Sciencecraft and Propulsion Module Pair (1 of 3) Dry Total	**801**	**30%**	**1041**
Propellant	527	CBE includes worse case launch date and 3 sigma dispersions on delta-v required, and dry mass including the 30% contingency	527
Sciencecraft and Propulsion Module Pair (1 of 3) Wet Total	**1328**		**1568**
Stack Total (3 pairs)	3983		4704
Launch Vehicle Adapter Total	163		212
Total Launch Mass	**4146**		**4916**
Launch Vehicle	Medium Lift EELV (Launch capability to the required C3 = 0.5 m^2/s^2 is 5165 kg.)		
Launch Site	KSC		
Launch Vehicle Mass Margin	249 kg (5%)		

Table 2-7c. Mission Design – Power (For One of Three Identical Sciencecraft)

Power	
Spacecraft Bus Power without contingency	358 W
Payload Power without contingency	253 W
Spacecraft Bus + Payload Power without contingency	611 W
Power Contingency	30%
Spacecraft Bus + Payload Power with contingency	794 W

2.3. Spacecraft Implementation

1. Describe the spacecraft characteristics and requirements. Include a preliminary description of the spacecraft design and a summary of the estimated performance of the key spacecraft subsystems. Please fill out the Spacecraft Mass Table.

The spacecraft bus is designed around the payload to provide a quiet, stable environment. A primary requirement during science operations is to provide a platform and control system with micronewton thrusters to work with the GRS as part of the DRS to keep the residual acceleration noise on the proof mass to the required level specified in Table A-4. The other main requirement is to act as a passive thermal shield to keep temperature fluctuations from both external (the Sun) and internal (the avionics) sources from disturbing the dimensional stability of the optical bench and GRS. The optical assembly (telescope, GRS, optical bench, etc) is contained within a thermal shield and is mounted via flexures to the bus bottom panel. The electronic boxes are mounted via bolted interfaces to inserts in the bottom and outer panels. Solar arrays are mounted to a fixed deck 3.0 m in diameter that shades the entire vehicle. The spacecraft is 1.1 m high, excluding the protrusion of the high gain antennas.

The spacecraft bus subsystems are listed in Table 2-8 and briefly described in the response to Q6 in this subsection. The bus is a straightforward design based on components with proven flight heritage. There are no extreme requirements for new bus technologies other than the micronewton thrusters in the propulsion system, which are discussed elsewhere.

A separable propulsion module provides the thrust needed during the cruise phase. It consists of a surrounding structure, propellant storage and a propulsion system suitable for the delta- V required by the transfer trajectory to the final operational orbits.

The sciencecraft and propulsion module mass budgets are given in Table 2-10a and Table 2-10b respectively. A detailed description of the spacecraft bus and propulsion module and their subsystems can be found in references [O-6, O-12].

2. Provide a brief description and an overall assessment of the technical maturity of the spacecraft subsystems and critical components. Provide TRL levels of key units. In particular, identify any required new technologies or developments or open implementation issues.

LISA technology readiness has been formally evaluated many times. Table 2-8 provides TRL assessments by the Project and by Aerospace Corporation in a recent independent review. Since LISA Pathfinder is such an extraordinary component of LISA technology development, TRLs at the start of Phase B are also given to anticipate the progress from LPF and the on-going ground-based technology development program.

Table 2-8. Technical Maturity of Spacecraft and Subsystems

		Current TRL		Phase B Start TRL		
		NASA	Aero-space	NASA	Aero-space	Rationale for TRL
Attitude Control System (ACS)	DRS Control Laws	6	N/A	7	N/A	Demonstrated on GP-B, TRIAD, & LPF
	Star Trackers	9	9	9	9	Used for acquisition only. µASC from DTU & Ball CT602 meets requirements
	Sun Sensors	9	9	9	9	Multiple heritage systems available, e.g. AeroAstro.
	Solid State Gyros	9	9	9	9	Baseline LN-200 IMU from Northrop Grumman. Options from EADS Astrium, Honeywell, & Litton Resonant Gyros.
Command & Data Handling		6	6	7	7	COTS components. Baseline CPU is BAE RAD750. Interfaces are MIL STD 1553 & SpaceWire.
Communications	High Gain Antenna & Gimbals	N/A	9	N/A	9	Heritage with MRO, Cassini, DS1, & others. Single-axis gimbals
	Traveling Wave Tube Amplifier	N/A	9	N/A	9	Heritage with MRO, Cassini, DS1, & others
Electrical Power	Battery	9	9	9	9	Multiple heritage Li-Ion batteries available
	Solar Array	9	9	9	9	Standard body-mounted, triple-junction GaAs. Solar array is backwired to reduce stray magnetic fields
Propulsion	Micronewton Thrusters	5-6	5-6	7	7	Both LPF thruster designs meet thrust capacity and noise requirements. Need to validate for extended lifetime of LISA mission.
	Bipropellant	8	8	8	8	No new technology required
Structures & Mechanisms	Structure	7	7	7	7	Standard construction techniques & materials. Detailed mechanical design performed including structural, thermal, optical, and self-gravity (STOP-G) models and finite-element model of launch stack.
	Separation System	6-7	7-9	7	7-9	Heritage systems available (e.g. Lightband, SAAB clamp band). Lower TRLs assume qualification of larger-diameter band. Existing qualified bands can be accommodated with alternate structural design at cost of increased mass.

3. Identify and describe the three lowest TRL units, state the TRL level and explain how and when these units will reach TRL 6.

The micronewton thrusters have a TRL of 5-6, the lowest of any of the spacecraft components. These are a LISA technology development item and two thruster options will fly on LISA Pathfinder. See discussion in Section 3.3 for details.

The DRS control laws for the attitude control system are currently rated at TRL 6 based on extensive modeling and simulation. Similar control laws will fly on LPF, raising their TRL to 7 by the start of Phase B.

The third lowest TRL item is the C&DH system, currently at TRL 6. LISA does not place any unique requirements on the C&DH system and preliminary designs indicate that off the shelf components are available to meet the LISA design. Normal development will bring the TRL of the C&DH to TRL 7 by the start of Phase B.

4. What are the three greatest risks with the S/C?

The top risks to the LISA mission are contained in the payload, not the spacecraft. The spacecraft design and the vast majority of subsystem components to implement the design are “flight proven”. The three risk items that follow for the spacecraft (Table 2-9), with the exception of μN thruster performance, are significantly below those of the payload.

Table 2-9. Spacecraft Risks

Risk	Mitigation
Microthrusters fail to meet LISA lifetime requirements.	▪ Aggressive development of three independent thruster technologies (2 ESA, 1 NASA) ▪ Identify and model life-limiting mechanisms, validate models ▪ Accelerated testing to validate models and develop mitigationsResiliency and redundancy built into the LISA design
Microthruster contamination degrades optical performance.	▪ Significant ground testing/measurement to correlate models and verify analysis results ▪ Colloid thruster can operate with a tighter beam with minor effect on thrust range if required ▪ Flight demonstration/validation on LPF
Unexpected thermal fluctuation noise sources degrade residual acceleration performance	▪ Implement design and construction techniques to minimize thermal noise sources and leaks ▪ Extensive and thorough ground test program to correlate models and verify analysis results ▪ Inclusion of any applicable LPF lessons learned into the LISA thermal design ▪ Adequate performance margin to account for unexpected sources

5. If you have required new S/C technologies, developments or open issues describe the plans to address them (to answer you may provide technology implementation plan reports or concept study reports).

The only new S/C technology is the micronewton thrusters. Two thruster designs will fly on LPF, both of which meet the LISA requirements for thrust capacity and thrust noise. Additional development is needed to validate these designs for the longer duration of the LISA mission. See the *Enabling Technology* section for further discussion.

6. Describe subsystem characteristics and requirements to the extent possible. Describe in more detail those subsystems that are less mature or have driving requirements for mission success. Such characteristics include: mass, volume, and power; pointing knowledge and accuracy; data rates; and a summary of margins. Comment on how these mass and power numbers relate to existing technology and what light weighting or power reduction is required to achieve your goals.

Most subsystems of the LISA spacecraft bus have standard requirements and the baseline design has substantial spaceflight heritage. So, they have mature and not particularly challenging designs. The exception is the micronewton thruster subsystem, but here the performance requirements have been met except for the demonstration of lifetime. No unique light weighting or power reduction is required for any subsystem. A detailed description of the bus and propulsion module and their subsystems can be found in references [O-6, O-12].

- **Attitude Control System (ACS):** maintains pointing during the cruise and safe modes and science-mode. The majority of the ACS has modest requirements; the more stringent pointing requirements are the responsibility of the Disturbance Reduction System (DRS) controls that use outputs from the payload to perform the drag free operation using the micronewton thrusters.
- **Command and data handling:** The command and data handling architecture employs a central processor unit within the On-board Computer (OBC) driving a standard serial bus. Processing power and data rate requirements are all easily handled by flight proven components.
- **Communications:** The modest 90 kbps downlink / 2 kbps uplink requirements are met with a hybrid X/Ka-band system using two 30 cm high gain antennas and six omnidirectional antennas employing flight proven components.
- **Electrical:** A Power Control & Distribution Unit (PCDU), body mounted triple junction GaAs solar array (783 W EOL), and a 1.04 KWhr Li-Ion battery in a conventional design easily meets the LISA power requirements.
- **Propulsion:** The S/C propulsion system consists of micronewton thrusters (enabling technology) and their associated electronics. The propulsion model uses a standard bi-propellant system.
- **Structures/Mechanisms:** The S/C structure will be a unique, yet straightforward design that uses standard construction techniques and materials (mostly aluminum honeycomb composite). There are no deployables and the only mechanism associated with the spacecraft are HGA gimbals and the separation system (clamp band).
- **Thermal:** Passive design employing standard sensors and survival heaters.
- **Harness:** Standard flight harness can be used, but harness layout will be more precisely controlled than for a typical mission due to self-gravity requirements.

7. Describe the flight heritage of the spacecraft and its subsystems. Indicate items that are to be developed, as well as any existing hardware or design/flight heritage. Discuss the steps needed for space qualification.

Please see answer to Question 2 in this subsection Table 2-8.

8. Address to the extent possible the accommodation of the science instruments by the spacecraft. In particular, identify any challenging or non-standard requirements (i.e. Jitter/momentum considerations, thermal environment/temperature limits etc).

The spacecraft bus is tightly integrated with the payload in order to achieve drag-free operation. The combination is called a sciencecraft, and the three sciencecraft together constitute the instrument. The Gravitational Reference Sensors (GRS) each contain a proof mass that is part of the science measurement, but is also used as an inertial reference for the Disturbance Reduction System (DRS). The DRS uses a set of control laws and the micronewton thrusters to minimize the residual forces on the GRS. Figure 2-1 shows the accommodation of the instrumentation in the spacecraft bus.

The main non-standard requirement is that the mass distribution surrounding the proof masses must be such that the residual static gravitational field “bias” is within the dynamic range of the GRS. This requirement will be met by keeping a detailed mass model of the components as they are integrated onto the sciencecraft and then nulling any residual acceleration by careful placement of trim masses. LISA Pathfinder has a similar requirement and will be testing and verifying the procedure as part of the Pathfinder mission.

Temperature stability of the optical assembly is a driving requirement (about 220μK/m/√Hz at 0.1 mHz is required inside the GRS electrode housing). The requirements are met by choosing thermally benign orbits, passive thermal shielding, and power stabilization of the electronics.

The magnetic field budget should be easily met by placing all the magnetic components far from the proof mass and including a modest amount of magnetic shielding or compensation.

S/C and telescope pointing are also driving requirements for the LISA S/C (5.7 nrad/√Hz within the measurement bandwidth). During science operations, S/C attitude and position are controlled by the DRS which has demonstrated the required performance through a number of high fidelity simulations. A number of design features are implemented to enable the controllers to meet these requirements:

- LISA does not contain any reaction wheels or other constantly moving parts.
- The solar array is body mounted.
- The high gain antennas make small re-pointings every 12 days.
- All other moving parts are also designed to meet the pointing and jitter requirements.

9. Provide a schedule for the spacecraft, indicate the organization responsible and describe briefly past experience with similar spacecraft buses.

A coordinated schedule, including a timeline for the spacecraft, is provided in the *Programmatics & Schedule* section. The spacecraft bus will be built in-house by NASA/Goddard. Goddard has 50 years of experience building, testing, and flying spacecraft.

10. Describe any instrumentation or spacecraft hardware that requires non US participation for mission success.

No non-US participation is required.

11. Fill out the Spacecraft Characteristics Table.

Note that LISA is comprised of three spacecraft and three separable propulsion modules. The mass tables below are given for one spacecraft and one propulsion module. A detailed mass budget can be found in reference [O-11].

Table 2-10a. Sciencecraft Mass Table (kg)

Spacecraft bus	Current Best Estimate (CBE)	Percent Mass Contingency	CBE Plus Contingency (kg)
Structures & Mechanisms	139.8	30%	181.7
Thermal Control	15.9	30%	20.7
Propulsion (Dry Mass)	39.3	30%	51.1
Attitude Control	7.1	30%	9.3
Command & Data Handling	45.3	30%	58.9
Telecommunications	42.2	30%	54.9
Power	37.1	30%	48.2
Cabling	21	30%	27.3
Total Spacecraft Dry Bus Mass	347.7	30%	452.0

Table 2-10b. Propulsion Module Mass Table (kg)

Propulsion Module	Current Best Estimate (CBE)	Percent Mass Contingency	CBE Plus Contingency (kg)
Structures & Mechanisms	231.9	30%	301.5
Propulsion (Dry Mass)	71.5	30%	93
Command & Data Handling	9.1	30%	11.8
Telecommunications	2.0	30%	2.6
Total Spacecraft Dry Bus Mass	314.5	30%	408.8

Table 2-11a. Sciencecraft Characteristics Table

Spacecraft bus	Value/Summary, units
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum
Number of articulated structures	2 High gain antennas
Number of deployed structures	0
Thermal Control	
Type of thermal control used	Passive/survival heaters
Propulsion	
Estimated delta-V budget, m/s	17.6 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Micronewton thrusters using cesium or colloidal fluid as propellant
Number of thrusters and tanks	3 thruster clusters, no tanks
Specific impulse of each propulsion mode, seconds	6000 s
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial and Constellation
Attitude control capability, degrees	1.7×10^{-6} science 1/7200 non-science
Attitude knowledge limit, degrees	1/3600
Agility requirements (maneuvers, scanning, etc.)	0.5×10^{-6} deg/s
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	Telescope Articulation (1 axis) High Gain Antenna (2 axes)
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	Science mode IMS: 0.03-1.8 nrad/√Hz Micronewton Thrusters - Maximum thrust: 30µN Resolution: 0.1µN Non-Science mode DTU Star Trackers - Accuracy: 1 arcsec at 3σ LN-200S IRU - Accuracy: Random Walk 0.07 to 0.15º/sq rt hr Coarse Sun Sensors - Accuracy: 5 deg
Command & Data Handling	
Spacecraft housekeeping data rate, kbps	2.3 kbps per S/C (7 kbps for the constellation)
Data storage capacity, Mbits	64,000Mbits
Maximum storage record rate, kbps	<20kbps
Maximum storage playback rate, kbps	90kbps
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Body Mounted
Array size, meters x meters	5.3 m^2

Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	Triple Junction GaAs
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	1300 W BOL, 915 W EOL
On-orbit average power consumption, watts	794 W
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	20 amp-hours

Table 2-11b. Propulsion Module Characteristics Table

Propulsion Module	Value/ Summary, units
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum
Number of articulated structures	0
Number of deployed structures	0
Thermal Control	
Type of thermal control used	Passive/survival heaters
Propulsion	
Estimated delta-V budget, m/s	1130m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	22N mono-prop (hydrazine) axial ACS thrusters, 445N bi-prop (NTO/Hydrazine) Liquid Apogee Engine (LAE)
Number of thrusters and tanks	8 x ACS thrusters, 1 x LAE, 2 x He tanks, 2 x NTO tanks, 4 x Hz tanks
Specific impulse of each propulsion mode, seconds	235 s for ACS thrusters, 325s for LAE.
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial
Attitude control capability, degrees	0.5
Attitude knowledge limit, degrees	1/360
Agility requirements (maneuvers, scanning, etc.)	None
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	High Gain Antenna (2 axes)
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	DTU Star Trackers: 1 arcsec at 3σ LN-200S IRU: Random Walk 0.07 to 0.15°/√hr Coarse Sun Sensors: 5° No actuators other than thrusters.
Command & Data Handling	From S/C bus
Power	From S/C bus

3. Enabling Technology

1. For any technologies rated at a Technology Readiness Level (TRL) of 5 or less, please describe the rationale for the TRL rating, including the description of analysis or hardware development activities to date, and its associated technology maturation plan.

2. Describe the critical aspect of the enabling technology to mission success and the sensitivity of mission performance if the technology is not realized.

3. Provide specific cost and schedule assumptions by year for Pre-Phase A and Phase A efforts that allow the technology to be ready when required.

Enabling technologies are interpreted here as technologies that form the core of the science measurement concept and for which no reasonable alternatives exist. Three LISA technologies that fit this definition are the Phase Measurement System (PMS), the Gravitational Reference Sensor (GRS), and the micronewton thrusters. These technologies are addressed in the three subsections below. In each subsection, we provide a brief overview of the technology followed by a response to the questions. Note that in response to Question 3, only NASA costs are considered. A more comprehensive discussion of LISA technology can be found in reference [O-3].

3.1. Phase Measurement System (PMS)

The PMS provides the "photons-to-bits" readout of the laser interferometer signals containing the gravitational-wave strain information and providing displacement and angular readout used in the drag-free control system. By measuring to microcycle accuracy the phase of the heterodyne beatnote between lasers with a wavelength of one micrometer, the PMS provides picometer-level sensitivity to displacements between the LISA sciencecraft.

Q1: The current NASA-assessed TRL for the PMS is 4-5, which is consistent with the independent assessment of 5 by Aerospace Corp. The rationale for this assessment is successful laboratory testing of a TRL 4 level PMS in a dedicated interferometric testbed at JPL [P-3]. The TRL 4 PMS has demonstrated linearity, laser frequency noise cancellation, clock noise transfer and correction, and weak-light phase locking with sufficient performance.

Maturation of the PMS is proceeding following the approach outlined in the 2005 LISA Technology Development Plan. A flight implementation study is underway for the PMS and has already produced an architecture, detailed parts list, and bill of materials for a TRL 6 version of the Instrument Processor Unit, the subsystem implementing the core digital signal processing algorithms. Further refinements of the PMS will continue to be evaluated at the JPL interferometer testbed. In parallel, the testbed and TRL 4 phasemeter will be used to study other aspects of LISA interferometry such as inter-spacecraft ranging and communication.

Q2: The performance of the PMS directly impacts both the drag-free control system and the primary science signal; it is critical that it meet requirements. Degradation in PMS performance (increased read-out noise) would cause an increase in the residual acceleration noise on the proof mass as well as a decrease in the precision with which the proof-mass positions could be tracked. Such degradation could significantly affect the scientific performance of the instrument. The strategy for mitigating the risk of increased phase measurement noise is to construct laboratory testbeds that produce optical interference signals used to evaluate PMS performance.

Q3: With the exception of the ultra-stable oscillator, which will be a flight procurement, TRL 6 versions of all PMS components are expected in 2012. The cost of this technology development is $1,632k in FY2010, $1,908k in FY2011, and $1,777k in FY2012 for a total of $5,317k by the end of Phase A.

3.2. Gravitational Reference Sensor (GRS)

The GRS provides the inertial reference points for measuring gravitational wave strain. The reference is in the form of a *proof mass* which falls freely inside the sciencecraft and is monitored by a combination of capacitive and interferometric sensors. The GRS must accurately monitor the position and orientation of the proof mass relative to the spacecraft without introducing disturbances that could mask gravitational wave signals.

Q1: The current NASA-assessed TRL level for the GRS is 5-6, which is slightly higher than the independent assessment of TRL 4-5 by Aerospace Corporation. The rationale for this assessment is extensive laboratory testing of GRS systems and components for LPF [S-7, S-8]. Although this testing has focused on meeting LPF requirements, which are slightly relaxed from those of LISA, the LPF GRS is designed to meet LISA requirements and the tests have been extended where possible to gain information in the LISA regime. A model of major contributors to residual acceleration noise has been developed and tested in the laboratory using an Engineering Model (EM) of the LPF GRS. A limit of $5\text{x}10^{-14}\text{m-s}^{-2}/\sqrt{\text{Hz}}$ at 1 mHz has been placed on residual acceleration of the proof mass due to unpredicted surface forces.

Maturation of GRS technology will continue to focus on validation of the LPF engineering and flight models during the run-up to LPF launch in 2011. It is important to note that many of the lessons learned from LPF are already benefitting the design of LISA.

Q2: Degradation in GRS performance (increased acceleration noise of the proof mass) would result in a decrease in LISA sensitivity, particularly at low frequencies. Loss of low-frequency performance would reduce LISA's ability to estimate source parameters and possibly reduce detection rates of certain sources. The response to Question 6 in Section 1 addresses this effect in more detail. Mitigation against GRS performance risk is based on a combination of redundancy, extensive ground testing, and heritage from LPF. All electrical components in each GRS are redundant. In addition, most of the scientific goals of the mission can be achieved in the event of a complete failure of a single GRS. Experience gained in ground testing using torsion pendulums, as well as that gained during the development and operation of the LPF GRS will provide a solid understanding of GRS performance.

Q3: GRS development is an ESA activity. There are no NASA expenditures in this area for the duration of Phase A.

3.3. Micronewton Thrusters

The micronewton thrusters provide fine spacecraft attitude and position control for drag-free flight and beam pointing to the distant spacecraft. The thrusters are operated continuously during science operations with their thrust levels set by the DRS control loops.

Q1: The current TRL of the micronewton thrusters has been assessed as 5-6 by both NASA and independently by Aerospace Corp. This rating is based on microthruster development for LPF. Three thruster technologies have been developed for LPF: colloid micronewton thrusters (CMNT) made by Busek Co. in the U.S., cesium slit field emission electric propulsion (FEEP) thrusters made by ALTA S.p.A. in Italy, and indium needle FEEP thrusters made by ARC Seibersdorf in Austria. Engineering models (EMs) of the CMNTs have demonstrated the required thrust noise and resolution through several direct and indirect measurements. In addition, a CMNT EM passed a 3400-hour life test (LPF requirement). The flight-model CMNTs were delivered to ESA in June of 2009 and are awaiting integration into LPF. Flight unit construction and qualification of the slit FEEPs is underway in Europe. The needle FEEPs will continue development but will not fly on LPF.

Maturation of microthruster technology is focused on verifying that LPF thrusters can meet LISA lifetime requirements. In the past three years, the three candidate technologies have accumulated over 50,000 hours of operation with multiple 3,000-hour class tests. These tests have helped to identify, develop, and verify comprehensive physics-based models of various failure modes and gradual wear mechanisms. None of the known lifetime-limiting mechanisms precludes either LPF microthruster technology from meeting the LISA lifetime requirement. Accelerated life tests are now underway to further characterize the life-limiting mechanisms and to identify and eliminate any remaining failure modes.

Q2: Degraded performance (increased thrust noise) of the micronewton thrusters would result in an increased acceleration noise of the proof masses. This would reduce LISA's low-frequency sensitivity with adverse impacts to parameter estimation and detection rates. Thruster failure could limit the lifetime of the mission. Mitigation against thruster degradation and failure includes multiple designs, redundant thruster clusters, extensive ground testing, and detailed modeling of thruster failure modes. High loop gains give rise to ample margins which reduce sensitivity to thruster noise.

Q3: Technology development for the micronewton thrusters is expected to continue through 2012, with lifetime tests continuing through Phase B. The current NASA allocation for technology development is \$870k in FY2010, \$900k in FY2011, and \$1600k in FY2012.

4. Mission Operations Development

1. Provide a brief description of mission operations, aimed at communicating the overall complexity of the ground operations (frequency of contacts, reorientations, complexity of mission planning, etc). Analogies with currently operating or recent missions are helpful. If the NASA DSN network will be used provide time required per week as well as the number of weeks (timeline) required for the mission.

The LISA mission consists of four distinct phases: Launch, Cruise, Commissioning and Science Operations. The duration, major activities, frequency of contacts, maneuvers and complexity are summarized below:

- **Launch Phase:** The three sciencecraft with their attached propulsion modules will be launched on a single medium lift EELV from Kennedy Space Center. The phase will last 30 days and includes separations of the launch stack from the launch vehicle and of the sciencecraft/propulsion module pairs from each other. The propulsion modules will be oriented for power generation and started on their cruise trajectories. Near constant contact will be required during separation events. All ops will be planned well in advance of launch.
- **Cruise Phase:** The sciencecraft/prop module pairs cruise to their respective operational orbits in 14 months with three major burns and touch-ups as necessary. Ground contact will be needed for tracking, occasional status checking and commanding around the time of burns. Maneuvers can be planned well in advance and are naturally staggered, resulting in lower workforce demands. After insertion in their final orbits at the end of the Cruise Phase, the sciencecraft are separated from their propulsion modules.
- **Commissioning Phase:** Lasting three months, the LISA Commissioning Phase is expected to generally follow the LISA Pathfinder Master Test Plan to check out drag-free control. Pointing and laser frequency acquisition for interferometric operation are accomplished in this phase. Initial checkout of science performance, notably with known "verification binaries," will be carried out. The frequency of contacts will mostly vary from daily to once every six days for each spacecraft with an eight-hour pass. Acquisition will require more intense ground control, but takes of order less than a day.
- **Science Operations Phase:** The primary science mission will last 60 months. The DSN will have eight-hour contacts with each spacecraft every six days. The single instrument has a single mode for observations. No maneuvers are needed. No orbital maintenance of the formation is required. In the event of a massive black hole binary coalescence, interruptions for routine maintenance operations will be suspended for a protected period of four days, and one or two additional downlinks will be carried out just before the merger time. Mergers are expected to happen a few times per year, and the mergers times will be predicted weeks in advance.

The operations concept [O-10] involves the DSN for interplanetary communications, a Mission Operations Center (MOC) and NASA and ESA Science Operations Centers (SOCs). The MOC conducts mission control, telemetry management, spacecraft management and navigation, as well as instrument monitoring for health assessment.

The MOC processes and archives science and science housekeeping data, and then passes them to the SOCs for instrument health assessment and analysis to extract information about the astrophysical sources and the gravitational waves themselves. The SOC assesses instrument health and recommends instrument maintenance and operations to the MOC.

Telemetry is generated at a rate between 4 and 5 kbps on each sciencecraft. On a daily basis the three spacecraft together will generate a total of about 1.3 Gbit/day. This is lower than the daily data volume for other observatory-class missions such as HST (18 Gbit/day) and Spitzer (5.6 Gbit/day).

The complexity of mission planning will be at its peak during pre-launch, when mission scenarios are planned including in depth launch activities and maneuvers, and during cruise phase when the commissioning activities are finalized. Routine maintenance operations are: HGA re-pointing every 12 days, laser frequency changes every few weeks, and control system resets and re-calibration as necessary. The first two can be planned when the launch date is approximately known, and scheduling for the last can be estimated from commissioning experience.

The LISA mission operations concept shares some aspects of operations with the GRACE Mission and the Wilkinson Microwave Anisotropy Probe (WMAP) Mission. The two identical GRACE satellites operate together to measure changes in the Earth's gravitational field. A microwave system continuously ranges the 220 km between the two spacecraft, accelerometers with some similarities to the LISA GRS, and a GPS receiver that is the basis for the LISA phasemeter design. The two spacecraft also constitute a single instrument making continuous measurements of their separation. However, the GRACE satellites started in near circular, 500 km polar orbits, and have executed maneuvers. They do not use DSN, and all data is usually downlinked from one of the two spacecraft.

WMAP is at L2. It made continuous microwave measurements with five instruments in a single mode, generated data at a rate roughly comparable to LISA, and downlinked to the DSN daily. But WMAP had multiple feeds and detectors, and a very different attitude control system.

2. Identify any unusual constraints or special communications, tracking, or near real-time ground support requirements.

LISA has no unusual constraints or special support requirements. The LISA operations phase is characterized by routine uplinks and downlinks with Earth once every six days per spacecraft. When a massive black hole merger happens, there will be a four day "protected" period with reduced interruptions to science observations and one or two extra downlinks in the last few hours before the merger. Merger events can be predicted several weeks in advance.

3. Identify any unusual or especially challenging operational constraints (i.e. viewing or pointing requirements).

LISA has no unusual or challenging operational constraints.

4. Describe science and data products in sufficient detail that Phase E costs can be understood compared to the level of effort described in this section.

The four levels of science data products and the workforce to support them are:

- Level-0 science data products: raw telemetries received and reformatted by MOC. Archived and distributed by Science Center.
- Level-1 science data products: basic TDI data streams, house-keeping measurements, orbital data. Generated by instrument scientists in MOC, archived and distributed by the Center.
- Level-2 science data products: primary GW data streams (TDI observables corrected for spurious accelerations and other instrument effects), spacecraft ephemerides, instrument noise models. Generated by Science Center analysts (2 FTEs) in collaboration with LISA

Science Team, using the LISA data system developed in Phases C/D. Archived and distributed by Science Center.

- Level-3 science data products: source catalogs of detected systems (including detection confidence, parameters, time series, potential optical counterparts), SMBH merger alerts, diffuse background estimates, pre-subtracted TDI time series, and software tools to enable the use and analysis of science data products by GIs and others in the astronomical community. Level-3 data will be generated by Science Center analysts (4 FTEs) in collaboration with Science Team and select Guest Investigators, using the LISA data system and computing resources. It will be continually updated and released to the wider astronomical community as gravitational-wave source candidates accumulate sufficient SNR (and therefore statistical confidence), over timescales of months. It will be archived and distributed by the Science Center.

All data products will be made public after a short proprietary period according to NASA guidelines (except for SMBH merger alerts, which will be issued as long as possible before the merger events by analyzing the inspiral signals). Estimates of the daily data volume from the sciencecraft and the total archive volume are given in the responses to Question #1 and 6 in this subsection, respectively.

5. Describe the science and operations center for the activity: will an existing center be expected to operate this activity?; how many distinct investigations will use the facility?; will there be a guest observer program?; will investigators be funded directly by the activity?

In Phase E, the LISA Science Center will be staffed at an average level of 10 FTEs. The Science Center will:

- Receive Level-1 science and engineering data from JPL MOC, and generate Level-2 science data, feeding back maintenance and troubleshooting information to MOC (2 FTEs and some Science Team support).
- Coordinate and participate in core LISA science analysis activities; release updates of Level-3 science data products; generate SMBH event alerts and provide scheduling requirements to MOC (4 FTEs).
- Maintain Level-0 to Level-3 science data archive, operate centralized computing resource for core science analysis, provide user documentation, support software tools (2 FTEs).
- Administer the LISA Guest Investigator program (solicit, evaluate, and select proposals; administer grants); coordinate all LISA E&PO, including GI program press releases (2 FTEs).

In Phases C/D, the LISA science center will develop and test the LISA data archive, software tools, and data-analysis system, building on prototype gravitational-wave search codes built by Science Team analysts. For details on data analysis algorithms and the status of their development, see reference [O-9]. Phase C/D Science Center development will employ 9 FTEs. NASA HQ will decide on competing and structuring the science center; it is plausible that it may be hosted as an extension of another existing science center. All LISA investigations (dozens of GW searches, hundreds of EM counterpart searches, many theoretical studies) will use the data products generated by the LISA science center.

The LISA project is committed to supporting a user community through its guest observer/investigator program. The LISA project has estimated its cost at $45 million total, but NASA HQ will make the decision on the actual size and cost. The GIs will:

- Participate in the core LISA science activities.

- Perform additional searches for more speculative GW sources.
- Conduct astronomical and astrophysical research to extract science from the LISA science products.
- Follow up LISA triggers with EM or neutrino observations.

Finally, we note that ESA will fund a separate European LISA Science Center, which will work in close collaboration with the NASA Science Center. The European counterpart however will not support a GI program.

6. Will the activity need and support a data archive?

The LISA Science Center will design, build and operate a data archive to distribute Level-0 to Level-3 science data products, and to provide access to ancillary multiwavelength data, including imaging and redshifts in fields where GW sources have been found. Because the overall volume of the LISA data and science products will be limited (less than 1 TB), the archive operation will require only modest resources.

Table 4-1. Mission Operations and Ground Data Systems Table

Downlink Information	**Value, units**
Number of Contacts per Day during science ops	1 downlink per spacecraft every 6 days
Downlink Frequency Band, GHz	Ka-Band at 32 GHz
Telemetry Data Rate(s), bps	90 kbps
S/C Transmitting Antenna Type(s) and Gain(s), DBi	0.30 m HGA with 37.5 dBi
Spacecraft transmitter peak power, watts.	58 W
Downlink Receiving Antenna Gain, DBi	DSN 34m antenna gain 79.7 dBi
Transmitting Power Amplifier Output, watts	16 W average
Uplink Information	**Value, units**
Number of Uplinks per Day during science ops	1 uplink per spacecraft every 6 days
Uplink Frequency Band, GHz	X-band at 7.2 GHz
Telecommand Data Rate, bps	2 kbps
S/C Receiving Antenna Type(s) and Gain(s), DBi	0.30 HGA with 24.5 dBi

5. Programmatics & Schedule

1. Provide an organizational chart showing how key members and organizations will work together to implement the program.

The LISA Project is a cooperative endeavor between ESA and NASA. It is part of NASA's Physics of the Cosmos Program and is a Large Mission candidate in the ESA Cosmic Visions scientific program. The project is currently in Formulation (Phase A). The Formulation Phase working agreement of 2004 defines preliminary division of responsibilities between NASA and ESA, as following:

- NASA: Spacecraft, LISA Instrument and Metrology Avionics System (LIMAS), System Integration & Testing, Launch Services, Mission Operations and U.S. science data processing segment.
- ESA: LISA Opto-mechanical Core System (LOCS), Propulsion Modules and ESA science data processing segment.

The working agreement calls for both Agencies to develop micronewton thrusters as a parallel technology development activity.

Before entering the implementation phase, the Agencies will evaluate if the above-mentioned division of responsibilities needs to be revised. An implementation phase agreement will be documented in an MOU where one Agency will have a lead role and mission success responsibility and the other Agency will work in a support role. With the assumption that the division of responsibilities remains consistent with the 2004 agreement, Figure 5-1 shows how the NASA project will be organized as the lead agency. Figure 5-2 shows how the ESA project will then be organized to deliver on their responsibilities. This example assumes the micronewton thrusters are provided by ESA. Each Agency will individually manage the procurement of the attributed mission elements and each project manager will be individually accountable for product delivery and meeting performance requirements for their deliverables. For this reason, the dash lines in the organization charts represent the management of interfaces between subsystems delivered by the partnering agency.

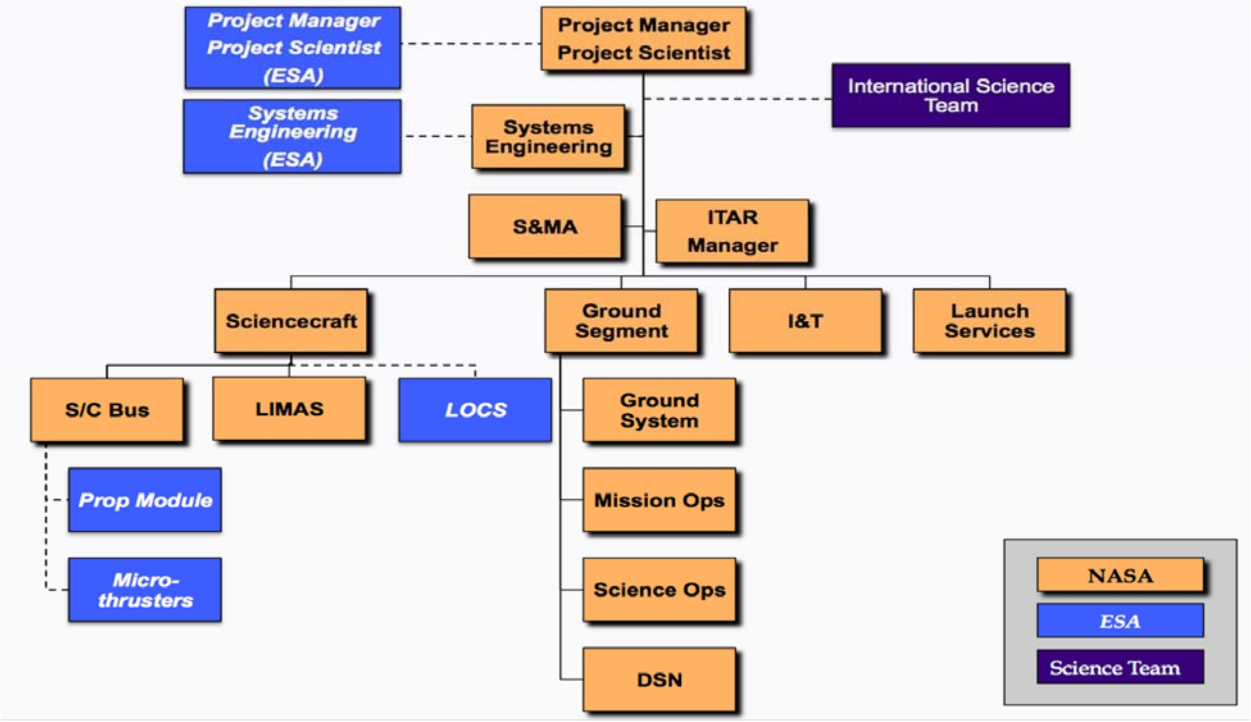


Figure 5-1. NASA Organization Structure in the Lead Role

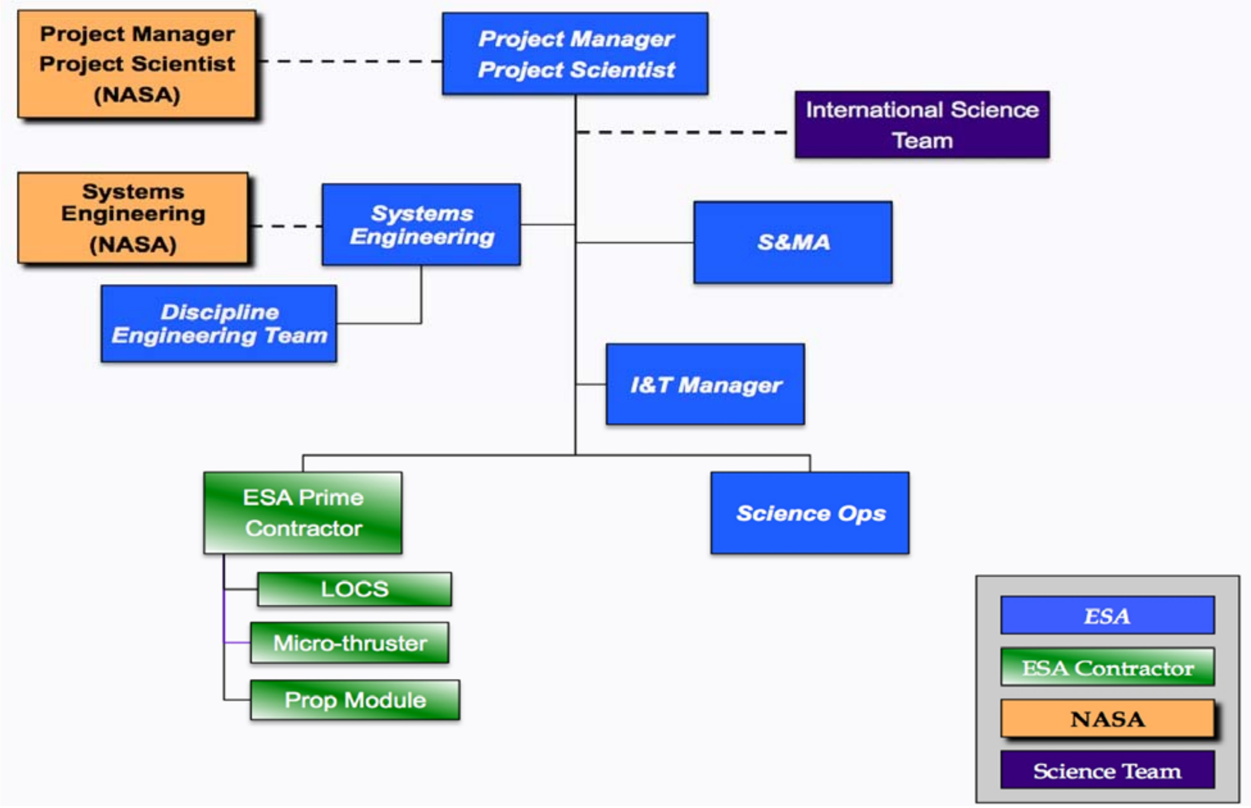


Figure 5-2. ESA Organization Structure in Support Role

2. Provide a table and a 5 by 5 risk chart of the top 8 risks to the program. Briefly describe how each of these risks will be mitigated and the impact if they are not. (Mass, power, schedule, money, science etc)

Table 5-1. Program Risk Table

ID	Risk	Mitigation
1	Complexity caused by multiple S/C development will impact schedule and cost.	▪ System I&T will not be a serial process ▪ All three S/C, P/L, and Prop Modules will be identical ▪ Two I&T teams and two GSE sets will be deployed ▪ Appropriate margin and flexibility will be incorporated into the schedule ▪ Will rely on ESA & NASA agency and industry past experience in developing multi-S/C programs such as CLUSTER, MMS, THEMIS
2	Complexity added by multiple agencies/centers will impact schedule and cost.	▪ Formulation phase activities are well coordinated ▪ Lessons learned from Formulation phase will be applied to Implementation Phase ▪ Clear roles and responsibilities will be defined ▪ Joint Project Management Plan and System Engineering Management Plan will be developed
3	Inability to perform end-to-end testing on the ground will result in degraded mission capabilities.	▪ DRS verification approach will be validated on LPF ▪ The three LISA S/C will perform their functions independently, so most of the system-level verification can be performed on each S/C independently ▪ Functional testing of inter-spacecraft interaction will be performed to verify the interferometers work closed loop ▪ Analytical models will be anchored to hardware testing in the lab
4	Failure of a single GRS system degrades science performance	▪ System is single-point failure tolerant by design. ▪ Direct flight heritage: LPF will fly the LISA GRS. ▪ Most science goals can be achieved with up to two GRS failures.
5	Microthrusters will fail to meet LISA lifetime requirements	▪ Aggressive development of two different thruster technologies (1 ESA, 1 NASA) ▪ Identify and model life-limiting mechanisms, validate models ▪ Accelerated testing to validate models and develop mitigations ▪ Resiliency and redundancy built into the LISA design
6	Loss of one S/C will cause the end of mission.	▪ All subsystems are required to be single-fault tolerant and most are fully redundant ▪ Up to two of the six inter-spacecraft links can fail with only minor degradation of overall performance ▪ Fault Detection, Isolation, and Recovery is being incorporated early in the design cycle

ID	Risk	Mitigation
7	LPF will fail to demonstrate some in-flight performance at the required levels or the data cannot be extrapolated to LISA performance.	▪ Redesign GRS based on LPF flight test results and experience ▪ Extend ground-test capability and re-test during 3 years prior to PDR
8	ITAR rules will limit the exchange of detailed technical information with ESA partners, risking mission success	▪ Capture experience from the previous projects such as LPF and JWST ▪ Define Implementation Phase roles and responsibilities that allow clear interface definitions that minimize the impact of ITAR ▪ Develop a solid ITAR plan early in the project lifecycle ▪ Obtain Implementation Phase license agreements and TAAs for the exchange of hardware and software between the agencies ▪ Identify ITAR-related milestones in the LISA Integrated schedule (such as Letter of Agreement (LOAs), MOUs, Export licenses, Technical Assistance Agreements (TAAs), etc) and identify early start times for preparatory activities leading to obtaining the said documents.

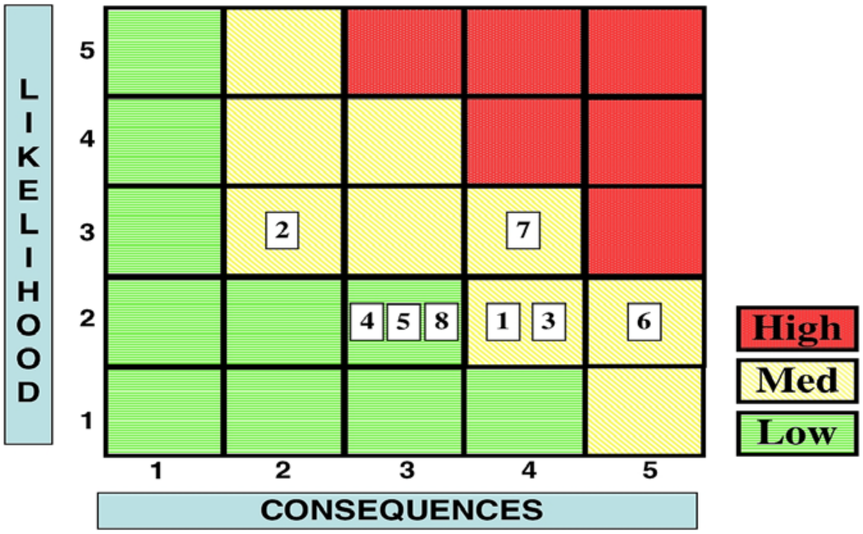
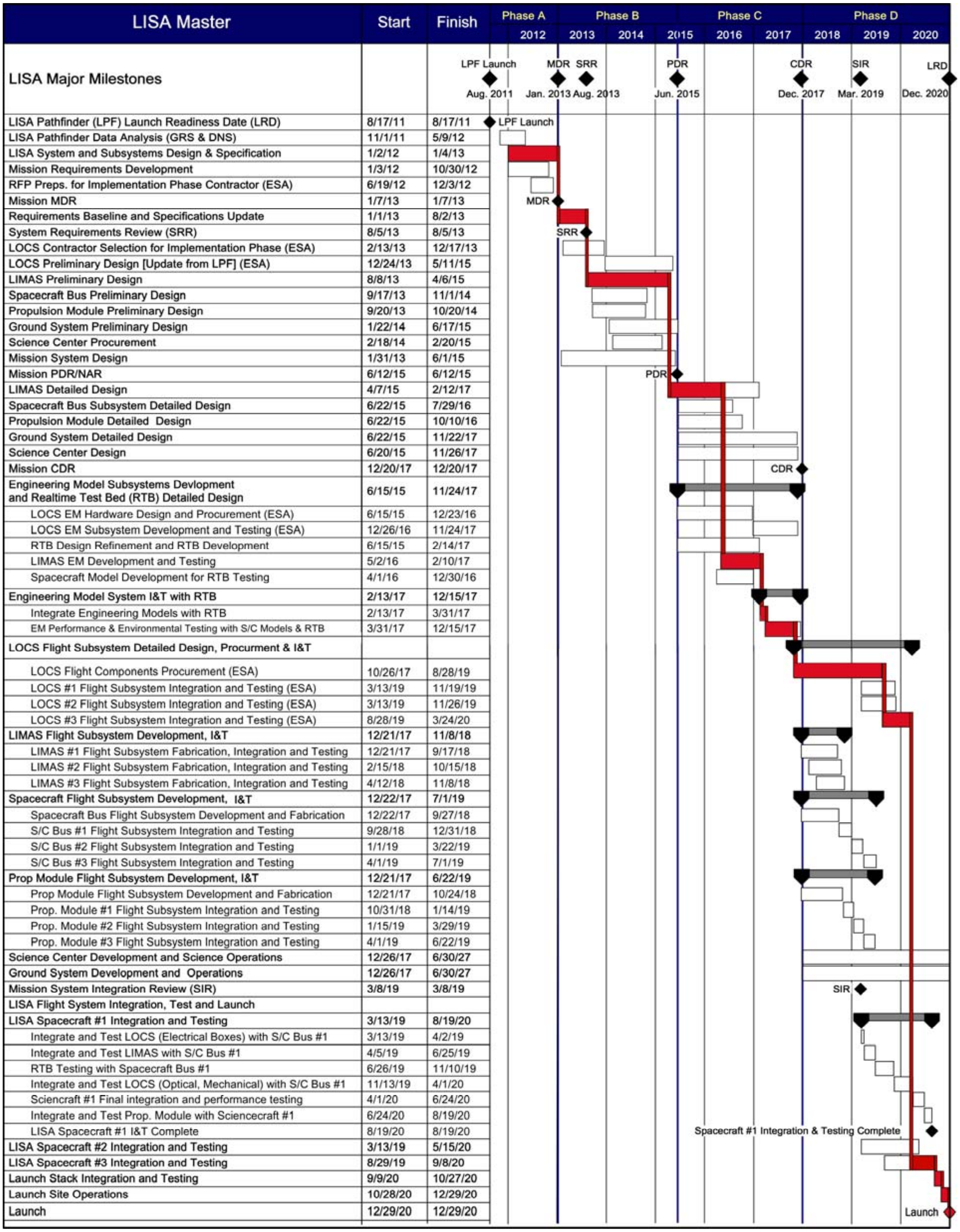


Figure 5-3. Program Risk Chart

3. Provide an overall (Phase A through Phase F) schedule highlighting key design reviews, the critical path and the development time for delivery required for each instrument, the spacecraft, development of ground and mission/science operations etc.

Figure 6-1 in Section 6 shows key elements of the LISA mission and a high-level integration flow for LISA elements and subsystems. The LISA Opto-mechanical Core System (LOCS) describes that part of the scientific instrumentation supplied by ESA in the 2004 Agreement, and the LISA Instrument and Metrology Avionics System (LIMAS) describes that part supplied by NASA. LOCS and LIMAS together constitute the payload. “Sciencecraft” is defined as the payload integrated with the spacecraft bus.

Figure 5-4 shows the schedule for Phase A through the end of Phase D. Phase E consists of 18 months of cruise and commissioning followed by 60 months of science operations. The critical path is shown in red in Figure 5-4. The schedule assumes that the project will continue the Phase A activities in FY-10, 11, and 12. LISA Pathfinder is scheduled to launch towards the end of 2011, with the data analysis completed before LISA enters Phase B. The schedule and the accompanying tables, as requested in this RFI, show the development and integration of three “sciencecraft”. Our current plan calls for two integration teams, working in parallel, to develop the three “sciencecraft” within the schedule presented here. The schedule includes eight months of funded reserve, which is currently held at the project manager level and has not yet been allocated and distributed to different phases or tasks. This allocation will occur later in the program as we approach towards completing our Phase A activities. For costing purposes however, the schedule reserve assumes the average burn rate during Phase C/D.



LISA Master	Start	Finish
LISA Major Milestones		
LISA Pathfinder (LPF) Launch Readiness Date (LRD)	8/17/11	8/17/11
LISA Pathfinder Data Analysis (GRS & DNS)	11/1/11	5/9/12
LISA System and Subsystems Design & Specification	1/2/12	1/4/13
Mission Requirements Development	1/3/12	10/30/12
RFP Preps. for Implementation Phase Contractor (ESA)	6/19/12	12/3/12
Mission MDR	1/7/13	1/7/13
Requirements Baseline and Specifications Update	1/1/13	8/2/13
System Requirements Review (SRR)	8/5/13	8/5/13
LOCS Contractor Selection for Implementation Phase (ESA)	2/13/13	12/17/13
LOCS Preliminary Design [Update from LPF] (ESA)	12/24/13	5/11/15
LIMAS Preliminary Design	8/8/13	4/6/15
Spacecraft Bus Preliminary Design	9/17/13	11/1/14
Propulsion Module Preliminary Design	9/20/13	10/20/14
Ground System Preliminary Design	1/22/14	6/17/15
Science Center Procurement	2/18/14	2/20/15
Mission System Design	1/31/13	6/1/15
Mission PDR/NAR	6/12/15	6/12/15
LIMAS Detailed Design	4/7/15	2/12/17
Spacecraft Bus Subsystem Detailed Design	6/22/15	7/29/16
Propulsion Module Detailed Design	6/22/15	10/10/16
Ground System Detailed Design	6/22/15	11/22/17
Science Center Design	6/20/15	11/26/17
Mission CDR	12/20/17	12/20/17
Engineering Model Subsystems Devlopment and Realtime Test Bed (RTB) Detailed Design	6/15/15	11/24/17
LOCS EM Hardware Design and Procurement (ESA)	6/15/15	12/23/16
LOCS EM Subsystem Development and Testing (ESA)	12/26/16	11/24/17
RTB Design Refinement and RTB Development	6/15/15	2/14/17
LIMAS EM Development and Testing	5/2/16	2/10/17
Spacecraft Model Development for RTB Testing	4/1/16	12/30/16
Engineering Model System I&T with RTB	2/13/17	12/15/17
Integrate Engineering Models with RTB	2/13/17	3/31/17
EM Performance & Environmental Testing with S/C Models & RTB	3/31/17	12/15/17
LOCS Flight Subsystem Detailed Design, Procurment & I&T		
LOCS Flight Components Procurement (ESA)	10/26/17	8/28/19
LOCS #1 Flight Subsystem Integration and Testing (ESA)	3/13/19	11/19/19
LOCS #2 Flight Subsystem Integration and Testing (ESA)	3/13/19	11/26/19
LOCS #3 Flight Subsystem Integration and Testing (ESA)	8/28/19	3/24/20
LIMAS Flight Subsystem Development, I&T	12/21/17	11/8/18
LIMAS #1 Flight Subsystem Fabrication, Integration and Testing	12/21/17	9/17/18
LIMAS #2 Flight Subsystem Fabrication, Integration and Testing	2/15/18	10/15/18
LIMAS #3 Flight Subsystem Fabrication, Integration and Testing	4/12/18	11/8/18
Spacecraft Flight Subsystem Development, I&T	12/22/17	7/1/19
Spacecraft Bus Flight Subsystem Development and Fabrication	12/22/17	9/27/18
S/C Bus #1 Flight Subsystem Integration and Testing	9/28/18	12/31/18
S/C Bus #2 Flight Subsystem Integration and Testing	1/1/19	3/22/19
S/C Bus #3 Flight Subsystem Integration and Testing	4/1/19	7/1/19
Prop Module Flight Subsystem Development, I&T	12/21/17	6/22/19
Prop Module Flight Subsystem Development and Fabrication	12/21/17	10/24/18
Prop. Module #1 Flight Subsystem Integration and Testing	10/31/18	1/14/19
Prop. Module #2 Flight Subsystem Integration and Testing	1/15/19	3/29/19
Prop. Module #3 Flight Subsystem Integration and Testing	4/1/19	6/22/19
Science Center Development and Science Operations	12/26/17	6/30/27
Ground System Development and Operations	12/26/17	6/30/27
Mission System Integration Review (SIR)	3/8/19	3/8/19
LISA Flight System Integration, Test and Launch		
LISA Spacecraft #1 Integration and Testing	3/13/19	8/19/20
Integrate and Test LOCS (Electrical Boxes) with S/C Bus #1	3/13/19	4/2/19
Integrate and Test LIMAS with S/C Bus #1	4/5/19	6/25/19
RTB Testing with Spacecraft Bus #1	6/26/19	11/10/19
Integrate and Test LOCS (Optical, Mechanical) with S/C Bus #1	11/13/19	4/1/20
Sciencraft #1 Final integration and performance testing	4/1/20	6/24/20
Integrate and Test Prop. Module with Sciencecraft #1	6/24/20	8/19/20
LISA Spacecraft #1 I&T Complete	8/19/20	8/19/20
LISA Spacecraft #2 Integration and Testing	3/13/19	5/15/20
LISA Spacecraft #3 Integration and Testing	8/29/19	9/8/20
Launch Stack Integration and Testing	9/9/20	10/27/20
Launch Site Operations	10/28/20	12/29/20
Launch	12/29/20	12/29/20

Figure 5-4. Integrated Schedule for Phases A Through D

4. Fill out the Key Phase Duration table indicating the length of time required (months) for: each Phase (A through F), ATP to PDR, ATP to CDR, and other key metrics for schedule analysis (ATP to instrument delivery, spacecraft delivery, observatory delivery and launch).

Table 5-2. Key LISA Phase Duration Table

Project Phase	Duration (Months)
Phase A – Conceptual Design	99 Months *(The Formulation Authorization Document (FAD) signed in October, 2004 formerly entered LISA into Phase A)*
Phase B – Preliminary Design	29 Months
Phase C – Detailed Design	30 Months
Phase D – Integration & Test	36 Months
Phase E – Primary Mission Operations	60 Months Nominal Science Operations *78 Months including 18 Months Cruise & Commissioning*
Phase F – Extended Mission Operations	36 Months
Start of Phase B to PDR	29 Months
Start of Phase B to CDR	59 Months
Start of Phase B to Delivery of Three (3) LIMAS Subsystems	FM #1 – 69 months FM #2 – 70 months FM #3 – 71 months
Start of Phase B to Delivery of Three (3) LOCS Subsystems	FM #1 – 73 months FM #2 – 73 months FM #3 – 77 months
Start of Phase B to Delivery of Three (3) Spacecraft Bus Subsystems	FM #1 – 72 months FM #2 – 75 months FM #3 – 78 months
Start of Phase B to Delivery of Three (3) Propulsion Modules Subsystems	FM #1 – 72 months FM #2 – 75 months FM #3 – 78 months
Start of Phase B to Delivery of Observatory (All 3 integrated Spacecraft delivered to I&T).	92 months
System Level Integration & Test	22 months
Project Total Funded Schedule Reserve	8 months
Total Development Time Phase B – D	Under 96 months
For LISA, the LISA instrument consists of a constellation of three Sciencecraft, each with two proof masses, separated by 5 million km and moving together in an equilateral triangle configuration in orbit around the sun at the same distance as the Earth. The three LOCS, LIMAS and Spacecraft Subsystems are the instrument's subsystems.	

5. Fill out the Key Event Dates table indicating the dates (month/year) for the key development and operations milestones.

Table 5-3. Key LISA Event Dates

Project Phase	**Milestone Date**
Start of Phase A	Oct. 2004
Start of Phase B	Jan. 2013
Preliminary Design Review (PDR)	June 2015
Critical Design Review (CDR)	Dec. 2017
Delivery of Three (3) LIMAS	FM #1 – Sept. 2018 FM #2 – Oct. 2018 FM #3 – Nov. 2018
Delivery of Three (3) LOCS	FM #1 – Nov. 2019 FM #2 – Nov. 2019 FM #3 – March 2020
Delivery of Three (3) Spacecrafts to I&T	FM #1 – Dec. 2018 FM #2 – March 2019 FM #3 – July 2019
Delivery of Three (3) Propulsion Modules to I&T	FM #1 – Jan. 2019 FM #2 – March 2019 FM #3 – June 2019
System Integration Review (SIR)	March 2019
Pre-Ship Review (PSR)	Oct. 2020
Launch Readiness Date (LRD)	Dec. 2020
End of Mission – Primary (EoM-P)	June 2027
End of Mission – Extended (EoM-E)	June 2030

6. Cost

6.1. Introduction

Before answering the specific questions being asked in this section, it is necessary to establish the context in which the questions are being answered. As requested in the cover letter, we have been asked to provide costing for three scenarios; the most probable, minimum and maximum practical contribution from the United States.

6.2. Background

Since the formal inception of the LISA project in 2001, five major costing exercises have been conducted to update the LISA mission Life Cycle Cost (LCC). The Project completed a parametric based analysis in 2003, followed by an independent assessment by Aerospace Corporation under the direction of the Technology Readiness & Implementation Review Team in the same year. SAIC, under the direction of the Beyond Einstein Program Assessment Committee (BEPAC), conducted the third major parametric-based estimate in 2007. In preparation of the Astro2010 review, the project embarked upon an extensive, bottoms-up grass-roots exercise in 2008 and Aerospace Corporation, under the direction of NASA headquarters, conducted a parametric-based cost and schedule assessment of the LISA mission in 2009. LISA's measurement concept and the mission architecture have remained constant throughout these exercises. With the exception of the BEPAC led estimate, all other estimates have been within 20% of each other at ~$1.2B (Real Years) for NASA's share. BEPAC estimated the total mission cost as $3.2B (Real Year). There was no interaction between the project and the BEPAC to understand or resolve the differences. The project in-house grassroots estimate of 2008 is within 5% of the Aerospace assessment results of 2009 at 70% confidence level.

We will use the project in-house estimate to answer the questions in this section because of the higher granularity of the data available to answer the questions. The Aerospace estimate will be shown as well as a comparison to our in-house estimate.

6.3. Approach for the Grassroots Estimate

Figure 6-1 shows the key cost elements of the LISA mission and a high-level integration flow. LISA projects at NASA and ESA developed grassroots estimates for all elements, sub-systems and components, regardless of the divisions specified in the 2004 agreement. NASA project did not attempt to estimate the bottoms-up cost of the GRS (a LOCS sub-system), since ESA has already invested extensive resources in developing this technology. It is not conceivable that NASA could take on the responsibility of this sub-system at this time. Cost estimates developed by NASA were produced by GSFC and JPL organizations with expertise in the given subsystem. ESA cost estimates are anchored to the development costs for LISA Pathfinder (LPF).

NASA project estimated the cost for the following elements:

- Mission Management, Mission Systems Engineering and Mission Assurance
- Mission Integration, Testing and Verification
- Spacecraft Bus
- Micronewton Thrusters
- Mission Operations
- NASA Science Operations
- Propulsion Module
- Launch Services

- Telescope (a subsystem of LOCS)
- Lasers (a subsystem of LOCS)

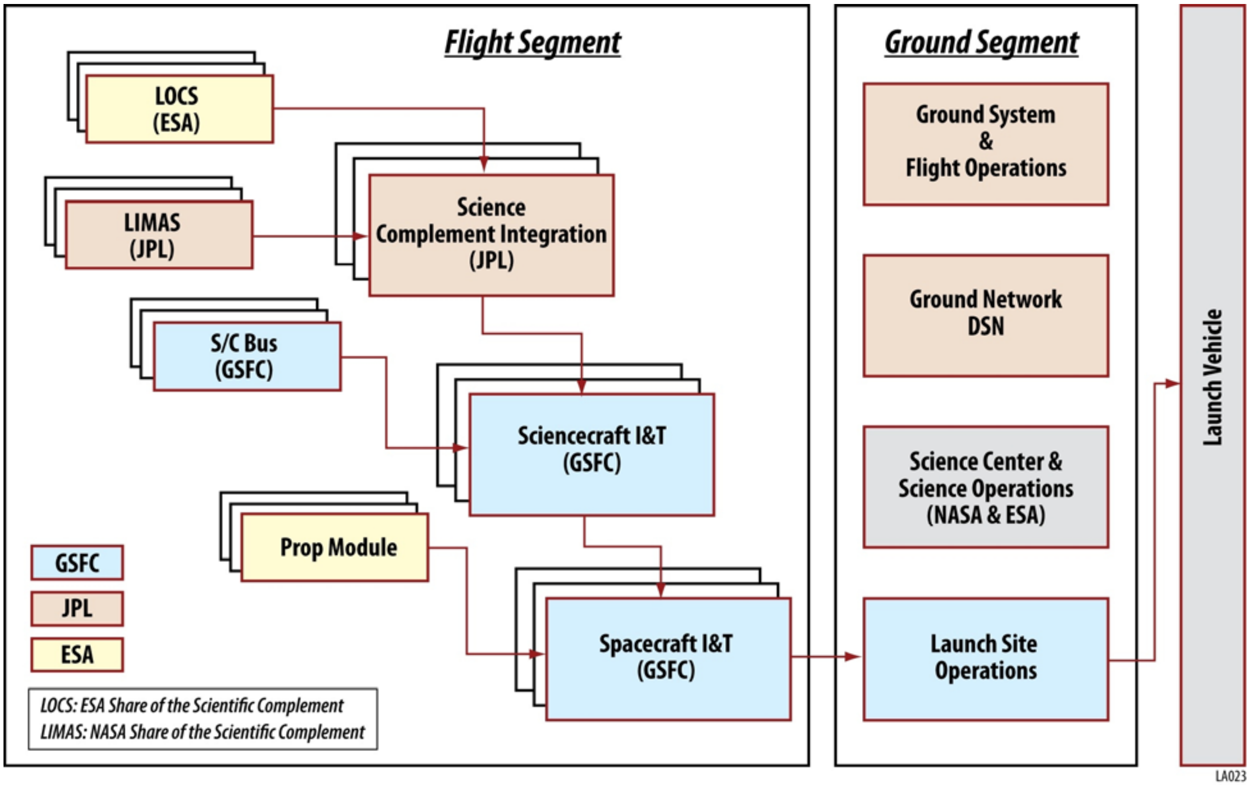


Figure 6-1. Key Elements of the LISA Mission and High-Level Integration Flow

6.4. Cost Estimate Database

A cost database was generated containing the detailed cost estimates for all of the above elements. Using this database, the NASA share of the mission cost can be calculated for any given scenario by adding together the line item costs for the elements allocated to NASA. Costs for Project Management, Systems Engineering, Mission Assurance and reserves can then be added as a factor of the sub-total of the element costs to determine the total mission life cycle cost. The three scenarios requested by this RFI will be presented using the approach outlined above. The assumptions behind the basis of this estimate for each element, as well as the resulting cost estimate for the element are provided in Appendix C.

6.5. Comparison with the Aerospace Independent Cost Estimate of 2009

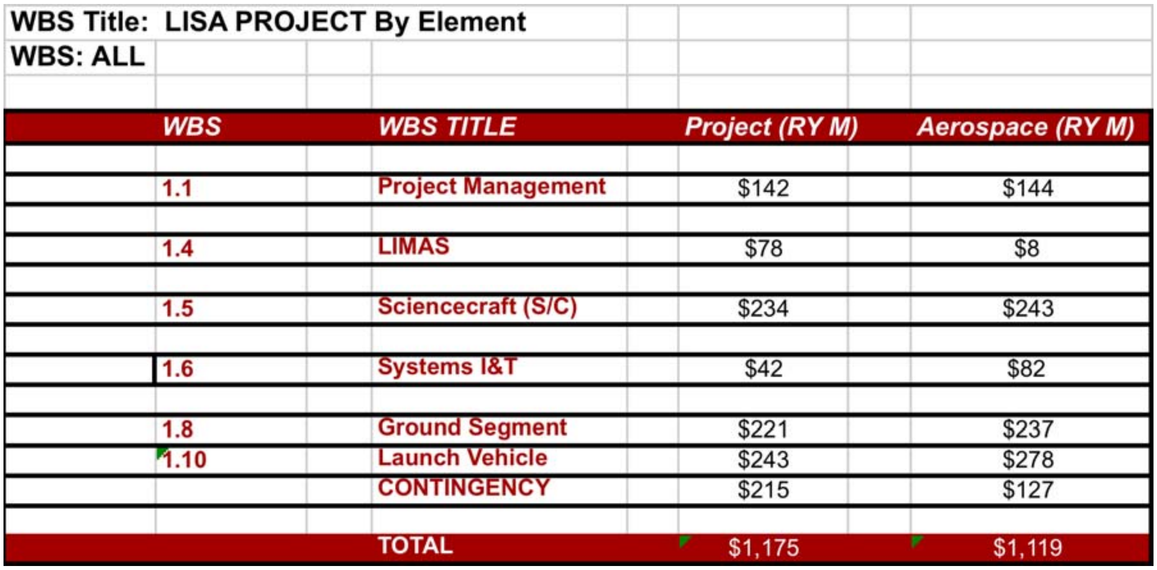
Table 6-1 shows a comparison between the project grassroots and the Aerospace parametric based cost estimates. The Aerospace estimate represents LISA mission cost at 70% confidence level. Aerospace also made an assessment of our schedule. Their independent schedule estimated a 98-month long phase B/C/D at 70% confidence level, compared to the project's estimate of 96 months.

In order to make the comparison, some cost elements for the project estimate had to be re-combined according to the WBS definition used by Aerospace Corporation. The Aerospace definition is summarized below:

- Project Management includes

  - Project Management
  - Mission Systems Engineering
  - S/C Bus Management & Systems Engineering
  - Safety & Mission Assurance
- Launch Vehicle includes
  - Launch Stack I&T
  - Launch Site Operations
- System I&T includes S/C Bus I&T
- Ground Segment also includes Mission Science & the Guest Investigator program

Table 6-1. In-house vs. Aerospace Cost Estimates



WBS Title: LISA PROJECT By Element

WBS: ALL

WBS	WBS TITLE	Project (RY M)	Aerospace (RY M)
1.1	Project Management	$142	$144
1.4	LIMAS	$78	$8
1.5	Sciencecraft (S/C)	$234	$243
1.6	Systems I&T	$42	$82
1.8	Ground Segment	$221	$237
1.10	Launch Vehicle	$243	$278
	CONTINGENCY	$215	$127
	TOTAL	$1,175	$1,119

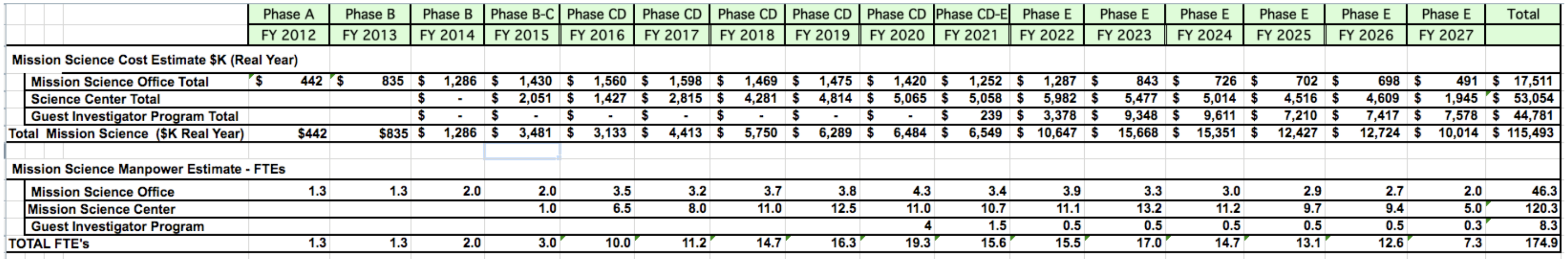
1. Provide manpower estimates and cost by year/Phase for all expected scientists that will be involved in the mission.

Cost for the Mission Science is categorized as follows:

- Mission Science Office; a part of the project office, including E&PO
- Mission Science Center; competitively selected by NASA
- Guest Investigator Program

Table 6-2 shows the cost and FTE breakdown for each of the categories mentioned above. The cost includes procurement requirements within each category. In the case of the Guest Investigator Program, the cost includes the grants dollars assumed for this costing exercise. The FTE numbers for the Guest Investigator program only represents the manpower required to manage the program. It should be noted that the FTE numbers in this table do not include the scientists involved in the project management, systems engineering, and the hardware development areas. Their cost is covered in the relevant WBS elements.

Table 6-2. Cost and FTE Breakdown by Category



	Phase A	Phase B	Phase B	Phase B-C	Phase CD	Phase CD	Phase CD	Phase CD	Phase CD	Phase CD-E	Phase E	Phase E	Phase E	Phase E	Phase E	Phase E	Total
	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	
Mission Science Cost Estimate $K (Real Year)																	
Mission Science Office Total	$ 442	$ 835	$ 1,286	$ 1,430	$ 1,560	$ 1,598	$ 1,469	$ 1,475	$ 1,420	$ 1,252	$ 1,287	$ 843	$ 726	$ 702	$ 698	$ 491	$ 17,511
Science Center Total			$ -	$ 2,051	$ 1,427	$ 2,815	$ 4,281	$ 4,814	$ 5,065	$ 5,058	$ 5,982	$ 5,477	$ 5,014	$ 4,516	$ 4,609	$ 1,945	$ 53,054
Guest Investigator Program Total			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 239	$ 3,378	$ 9,348	$ 9,611	$ 7,210	$ 7,417	$ 7,578	$ 44,781
Total Mission Science ($K Real Year)	$442	$835	$ 1,286	$ 3,481	$ 3,133	$ 4,413	$ 5,750	$ 6,289	$ 6,484	$ 6,549	$ 10,647	$ 15,668	$ 15,351	$ 12,427	$ 12,724	$ 10,014	$ 115,493
Mission Science Manpower Estimate - FTEs																	
Mission Science Office	1.3	1.3	2.0	2.0	3.5	3.2	3.7	3.8	4.3	3.4	3.9	3.3	3.0	2.9	2.7	2.0	46.3
Mission Science Center				1.0	6.5	8.0	11.0	12.5	11.0	10.7	11.1	13.2	11.2	9.7	9.4	5.0	120.3
Guest Investigator Program									4	1.5	0.5	0.5	0.5	0.5	0.5	0.3	8.3
TOTAL FTE's	1.3	1.3	2.0	3.0	10.0	11.2	14.7	16.3	19.3	15.6	15.5	17.0	14.7	13.1	12.6	7.3	174.9

2. If ESA or another key partner is assumed to be a partner or a major contributor, provide an estimate by year and Phase for the breakdown between NASA and ESA (or other) contributions. This should be separate, but consistent with Total Mission Cost Funding Table.

ESA cost information is procurement sensitive at this time. ESA will be initiating a competitive selection process to select two contractors for the Phase B activities of the responsibilities assigned to ESA. For this reason ESA is not ready to make their cost data public at this time. As stipulated in the Cosmic Visions (CV) Program, where the ESA project resides, a budget of 650 M€ (FY2007 economic conditions) is allocated for a large mission (such as LISA) in the program.

The following is a reproduction of the statements made by the ESA project manager to the members of the Particle Astrophysics and Gravitation (PAG) panel at the Pasadena decadal meeting in May 2009.

- *The European funding for the L1 mission is guaranteed by the existence of the CV Program itself.*
- *The LISA project has a detailed analysis of the costs of the European part under several cooperative scenarios.*
- *The Cost at Completion fits the available envelope in all cases.*
- *The level of commitment will be according to inter-Agency agreements that will be stipulated after the selection process is completed and formalized in the MOU.*
- *LISA is a very serious candidate for L1.*

All the cooperative scenarios considered by ESA for the costing of their part take into account the case of NASA or ESA in the lead. For all the cases considered, the ESA worst case cost is within the L1-class financial envelope of 650 M€ (FY2007 economic conditions).

In answering this question, only NASA cost will be presented for the three scenarios requested by this RFI. The allocation of responsibilities used in the three scenarios presented here were developed in cooperation with the ESA project. In all three cases, ESA can deliver their share within their budget allocation of 650 M€.

The three cost scenarios are defined as following:

1. **Most Probable US Contribution**: Assumes the division of responsibilities defined in the 2004 agreement and assumes NASA as the lead agency.
2. **Maximum practical US contribution**: Assumes NASA is responsible for delivering all LISA subsystems, except the GRS.
3. **Minimum practical US contribution**: Assumes that ESA commitment of 650 M€ is fully utilized. In this scenario, this assumes ESA as the lead agency, responsible for delivering the P/L, the PM and the micropropulsion and performing the system-level integration and testing. NASA is responsible for providing the remaining deliverables, which in this scenario includes the spacecraft bus, LIMAS, and the launch services.

Table 6-3 shows division of responsibilities assumed for determining the US cost for the three scenarios and Table 6-4 shows the resulting cost, including Project Management, Systems Engineering, Mission Assurance, and reserves.

Table 6-3. NASA/ESA Division of Responsibilities – Three Scenarios

Mission Elements	Most Probable		Maximum Practical		Minimum Practical	
	ESA	NASA	ESA	NASA	ESA	NASA
Mission Leadership		✓		✓	✓	
LOCS Subsystems						
GRS	✓		✓		✓	
Laser	✓			✓	✓	
Telescope	✓			✓	✓	
LIMAS		✓		✓		✓
Spacecraft Bus		✓		✓		✓
Propulsion Module	✓			✓	✓	
Micropropulsion	✓			✓	✓	
System I&T		✓		✓	✓	
Ground System & Operations		✓		✓	✓	
Launch Services		✓		✓		✓
Science Center/Guest Investigator	✓	✓	✓	✓	✓	✓

Table 6-4. Estimate of NASA Cost - Three Scenarios

$ K (Real Year Dollars) ITEM	Most Probable	Maximum Practical	Minimum Practical
Phase A Concept Study	11,078	11,078	11,078
Science (Pre launch)	32,837	32,881	32,837
LOCS Sub System	0	90,000	0
LIMAS	70,329	70,329	70,329
Thrusters		85,000	
Propulsion Module		81,000	
Spacecraft	263,293	263,293	263,293
Ground Data System Development	54,710	54,710	
MSI&T	23,602	23,602	
Launch Services	243,400	243,400	243,400
Education/Outreach (from Science) thru Phase D	2,784	4,222	2,331
MO&DA			
Science (Post Launch)	80,646	80,646	80,646
Engineering Support	2,175	2,175	0
Mission Operations	52,027	52,027	0
Education/Outreach (from Science) Phase E	665	665	405
SUB TOTAL HARDWARE & OPERATIONS	837,546	1,095,028	704,320
PM/SE/MA (less Instrument PM/SE)	101,535	121,568	90,114
PM/SE/MA (MO&DA Phase E)	24,200	24,200	8,105
Instrument PM/SE	7,814	17,814	7,814
SUB TOTAL HDWE, OPS and MNGT	971,095	1,258,610	810,353
RESERVES			
Development	166,477	235,054	147,113
MO&DA	48,587	48,587	13,373
TOTAL COST $K (RY) PHASE A-D	977,859	1,333,951	868,310
TOTAL COST $K (RY) PHASE E	208,300	208,300	102,530
TOTAL MISSION COST $K (RY)	1,186,159	1,542,251	970,840
SPACECRAFT Including MSI&T	286,895	286,895	263,293
TOTAL DEVELOPMENT w/o Reserves	556,904	844,419	466,719
TOTAL PHASE A-D Development Cost	723,381	1,079,473	613,832
MO&DA (No Reserve, No E&O)	159,048	159,048	88,751
Education and Outreach (PHASE A-E)	3,449	4,887	2,736

3. Provide a description and cost of what will be performed during Phase A by year. Also include total length of Phase A in months and total Phase A estimated costs.

LISA project has been in Phase A since 2004. Together with the ESA project, we have made a steady progress towards maturing the mission science requirements and the mission architecture to meet the requirements, even with the minimal funding received since 2004. We expect that the low-level funding will continue in FY10 & 11. Based on the budget guidelines provided by NASA headquarters, we expect the funding level to increase starting FY 12. Assuming this funding profile, the project expects to complete Phase A in 2013, as indicated in the master schedule provided herein. The available funding will be allocated to the remaining technology development as well as developing the required Phase A products required by NPR7120.5.D Following is a summary of the key Phase A activities.

Technology development activities will bring micronewton thruster head and micro-valve combination to TRL 6 by accomplishing the following:

- Accelerated testing of ST7 and LISA thruster components
- Development, validation, and verification of key failure models
- Procurement of prototype thruster head system components for testing
- Performance measurements (thrust range, precision, noise and contamination)

We will initiate thruster life testing with the goal of demonstrating 40000 hrs, with a prototype LISA Colloid thruster system, by PDR.

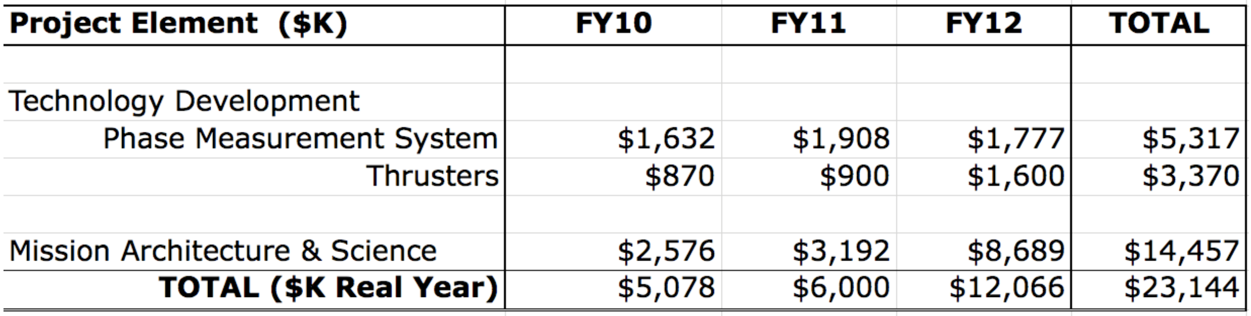
We will also develop TRL-6 versions of LIMAS by 2012.

Formulation activities will include:

- Second iteration of mission design
- Requirement flow-down to subsystems
- ICD development
- Systems Engineering Management Plan development
- Project Plan development
- I&T Plan development
- Formalizing ITAR Plan
- Formalizing division of responsibilities between NASA & ESA
- Update and refine the Science Requirements Document
- Develop enhanced tools for calculating LISA science performance for Extreme Mass Ratio Inspirals
- Continue work on definition and implementation of the Mock LISA Data Challenges
- Convene LISA International Science Team meetings
- Develop requirements for a US LISA Science Center

Table 6-5 shows the funding allocation planned for the activities described above.

Table 6-5. Funding Allocation for Mission Architecture and Mission Science

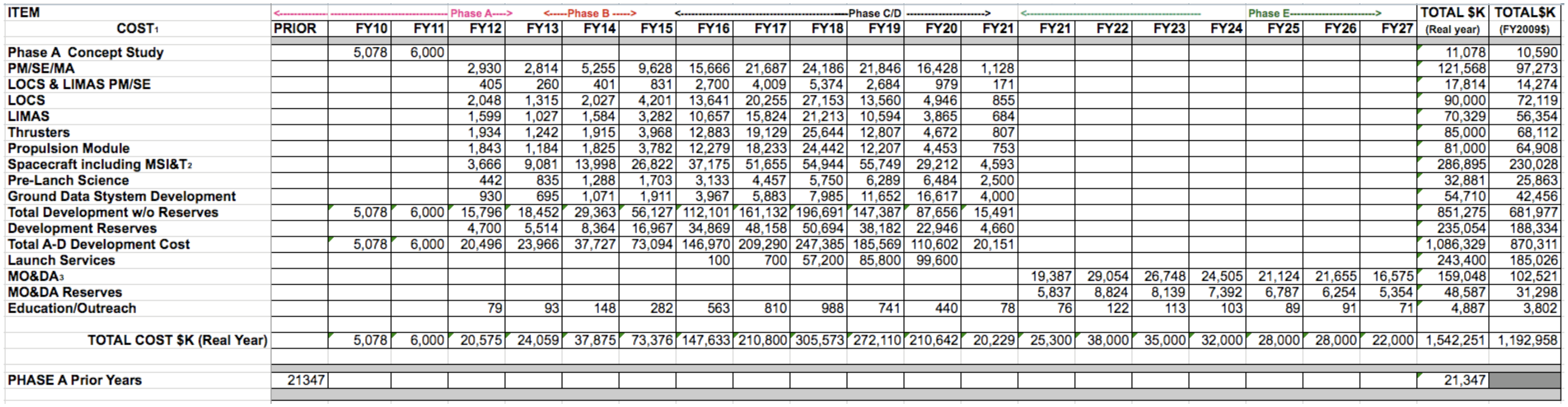


Project Element ($K)	**FY10**	**FY11**	**FY12**	**TOTAL**
Technology Development				
Phase Measurement System	$1,632	$1,908	$1,777	$5,317
Thrusters	$870	$900	$1,600	$3,370
Mission Architecture & Science	$2,576	$3,192	$8,689	$14,457
TOTAL ($K Real Year)	$5,078	$6,000	$12,066	$23,144

4. Please fill out the Mission Cost Funding Profile table assuming that the mission is totally funded by NASA and all significant work is performed in the US.

Table 6-6 is populated with the US cost data for the "Maximum Practical" scenario, which assumes that ESA is responsible for the GRS and the European portion of the science center. This table is only missing the cost for the GRS, which is assumed to include the optical bench, and therefore is the best possible representation of the total mission cost if only the US was responsible for the mission.

Table 6-6. Maximum Practical Mission Cost Funding Profile – US Only



ITEM	<--------------	---------------------------------- Phase A---->			<-----Phase B ----->			<--Phase C/D	--------------------->					<--				Phase E------------------------->			TOTAL $K	TOTAL$K
COST[1]	PRIOR	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY21	FY22	FY23	FY24	FY25	FY26	FY27	(Real year)	(FY2009$)
Phase A Concept Study		5,078	6,000																		11,078	10,590
PM/SE/MA				2,930	2,814	5,255	9,628	15,666	21,687	24,186	21,846	16,428	1,128								121,568	97,273
LOCS & LIMAS PM/SE				405	260	401	831	2,700	4,009	5,374	2,684	979	171								17,814	14,274
LOCS				2,048	1,315	2,027	4,201	13,641	20,255	27,153	13,560	4,946	855								90,000	72,119
LIMAS				1,599	1,027	1,584	3,282	10,657	15,824	21,213	10,594	3,865	684								70,329	56,354
Thrusters				1,934	1,242	1,915	3,968	12,883	19,129	25,644	12,807	4,672	807								85,000	68,112
Propulsion Module				1,843	1,184	1,825	3,782	12,279	18,233	24,442	12,207	4,453	753								81,000	64,908
Spacecraft including MSI&T[2]				3,666	9,081	13,998	26,822	37,175	51,655	54,944	55,749	29,212	4,593								286,895	230,028
Pre-Lanch Science				442	835	1,288	1,703	3,133	4,457	5,750	6,289	6,484	2,500								32,881	25,863
Ground Data Stystem Development				930	695	1,071	1,911	3,967	5,883	7,985	11,652	16,617	4,000								54,710	42,456
Total Development w/o Reserves		5,078	6,000	15,796	18,452	29,363	56,127	112,101	161,132	196,691	147,387	87,656	15,491								851,275	681,977
Development Reserves				4,700	5,514	8,364	16,967	34,869	48,158	50,694	38,182	22,946	4,660								235,054	188,334
Total A-D Development Cost		5,078	6,000	20,496	23,966	37,727	73,094	146,970	209,290	247,385	185,569	110,602	20,151								1,086,329	870,311
Launch Services								100	700	57,200	85,800	99,600									243,400	185,026
MO&DA[3]														19,387	29,054	26,748	24,505	21,124	21,655	16,575	159,048	102,521
MO&DA Reserves														5,837	8,824	8,139	7,392	6,787	6,254	5,354	48,587	31,298
Education/Outreach				79	93	148	282	563	810	988	741	440	78	76	122	113	103	89	91	71	4,887	3,802
TOTAL COST $K (Real Year)		5,078	6,000	20,575	24,059	37,875	73,376	147,633	210,800	305,573	272,110	210,642	20,229	25,300	38,000	35,000	32,000	28,000	28,000	22,000	1,542,251	1,192,958
PHASE A Prior Years	21347																				21,347	

5. For those partnering with ESA, JAXA, or other organizations, provide a second Mission Cost Funding Profile table and indicate the total mission costs clearly indicating the assumed NASA and contributed costs.

Table 6-7 presents the cost profile for the most probable cost scenario. This scenario assumes division of responsibilities according to the 2004 agreement.

ESA cost data is procurement sensitive at this time and is not provided in this table. In this scenario, ESA delivers the entire LOCS, Propulsion Module, micronewton thrusters, and the ESA Science Center. All of these elements fit within the budget allocation prescribed in the ESA Cosmic Visions Program.

Table 6-7. Most Probable Mission Cost Funding Profile – US Only

ITEM	<------	------	------	Phase A---->	<-----Phase B	----->		<------	------	------	------Phase C/D	------	------>	<------	------	------	------	Phase E------	------	------>	TOTAL $K	TOTAL $K
COST[1]	PRIOR	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY21	FY22	FY23	FY24	FY25	FY26	FY27	(Real year)	(FY2009$)
Phase A Concept Study		5,078	6,000																		11,078	10,590
PM/SE/MA				2,447	2,833	4,367	7,988	12,944	18,035	20,143	18,208	13,634	936								101,535	81,290
LIMAS PM/SE				178	114	176	365	1,184	1,758	2,357	1,177	429	76								7,814	6,261
LOCS																					0	0
LIMAS				1,599	1,027	1,584	3,282	10,657	15,824	21,213	10,594	3,865	684								70,329	56,354
Thrusters																					0	0
Propulsion Module																					0	0
Spacecraft including MSI&T[2]				3,666	9,081	13,998	26,822	37,175	51,655	54,944	55,749	29,212	4,593								286,895	230,036
Pre-Lanch Science				442	835	1,288	1,703	3,133	4,413	5,750	6,289	6,484	2,500								32,837	25,827
Ground Data Stystem Development				930	695	1,071	1,911	3,967	5,883	7,985	11,652	16,617	4,000								54,710	42,456
Total Development w/o Reserves		5,078	6,000	9,262	14,585	22,483	42,071	69,060	97,568	112,392	103,669	70,241	12,789								565,198	452,814
Development Reserves				2,756	4,358	6,404	12,718	21,493	29,242	33,843	31,010	20,806	3,847								166,477	132,872
Total A-D Development Cost		5,078	6,000	12,018	18,943	28,887	54,789	90,553	126,810	146,235	134,679	91,047	16,636								731,675	585,686
Launch Services								100	700	57,200	85,800	99,600									243,400	185,026
MO&DA[3]														19,387	29,054	26,748	24,505	21,124	21,655	16,575	159,048	102,521
MO&DA Reserves														5,837	8,824	8,139	7,392	6,787	6,254	5,354	48,587	31,298
Education/Outreach				47	73	113	211	347	490	565	521	353	64	76	122	113	103	89	91	71	3,449	2,650
TOTAL COST $K (Real Year)		5,078	6,000	12,065	19,016	29,000	55,000	91,000	128,000	204,000	221,000	191,000	16,700	25,300	38,000	35,000	32,000	28,000	28,000	22,000	1,186,159	907,181
PHASE A Prior Years	21347																				21,347	▨

CONTRIBUTIONS	PRIOR	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY21	FY22	FY23	FY24	FY25	FY26	FY27	(Real year)	(FY2009$)
Phase A Concept Study	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
PM/SE/MA	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
LIMAS PM/SE	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
LOCS	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
LIMAS	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Thrusters	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Propulsion Module	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Spacecraft including MSI&T[2]	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Pre-Lanch Science	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Ground Data Stystem Development	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Total Development w/o Reserves	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Development Reserves	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Total A-D Development Cost	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Launch Services	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
MO&DA[3]	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
MO&DA Reserves	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Education/Outreach	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
TOTAL CONTRIBUTIONS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																				TOTAL MISSION COST		

▨ = No data provided

[1] Costs should include all costs including any fee

[2] MSI&T - Mission System Integration and Test and preparation for operations

[3] MO&DA - Mission Operations and Data Analysis

7. Changes Since Previous NRC Recommendation

Activities ranked in either the 2000 "Astronomy and Astrophysics in the New Millennium" survey or in the "Beyond Einstein Program Assessment Committee" should provide up to four (4) additional pages describing the changes in the activity science goals, technical implementation, and/or estimated cost since AANM and the most recent previous NRC report. We need to understand your explanation of changes that significantly affect the scientific return, the activity risk, and/or estimated cost of the activity, and the reasons for them.

The LISA mission concept has been reviewed by both the previous decadal committee, Astronomy and Astrophysics in the New Millennium (AANM), in 2000 and the Beyond Einstein Program Assessment Committee (BEPAC) in 2007. Between these two reviews, the definition and design of the LISA mission matured significantly.

AANM endorsed LISA as the first new start after GLAST (now Fermi) among the moderate space-based initiatives. The concept had been studied at a low level for more than a decade beforehand [S-2]. The AANM "envisioned" a technology demonstration mission, and cited the computation of waveforms from merging black holes as an appropriate theory challenge. The co-evolution of massive black holes and their host galaxies had not gained widespread acceptance.

Following the AANM, the LISA Project Office was formed in 2000 and 2001, and the NASA/ESA agreement on roles and responsibilities was established in 2004. By the time the BEPAC got underway in November 2006, the LISA Project had been operating in Formulation phase for two years. LISA Pathfinder and ST-7, the LISA technology demonstration mission, were 6 months past PDR. The joint ESA-NASA Project team had detailed the conceptual design to an unusual degree with major contributions from Astrium GmbH, ESA's formulation study contractor. [Nearly a thousand pages of documentation were submitted to the BEPAC, and are available upon request.]

The BEPAC's principle finding with regard to LISA was: "Finding 4. LISA is an extraordinarily original and technically bold mission concept that will open up an entirely new way of observing the universe, with immense potential to enlarge the understanding of physics and astronomy in unforeseen ways. LISA, in the committee's view, should be the flagship mission of a long-term program addressing Beyond Einstein goals." The BEPAC recommended that a new start for LISA should take into account Pathfinder results, and that further technology and risk reduction investments would help ensure that NASA was well-positioned for that start.

In the subsections that follow, we discuss in more detail advances in LISA science, progress in technical implementation, and the evolution of LISA cost estimates.

7.1. Science Goals

The principal science performance goals, described in the Science Overview and in [O-7], have been remarkably stable over the last decade. Initially, these requirements were derived by considering the various types of GW sources and estimating what level of signal-to-noise (SNR) was required for LISA to yield important scientific results. Over the last decade, the analytical tools available to calculate science performance have increased dramatically in sophistication. It is gratifying that our initial estimates of the required sensitivity have been validated by these more sophisticated methods.

Analysis Algorithms and Tools for Estimating Science Performance. Ten years ago, our estimates of the science performance of LISA used rather simple models of gravitational wave (GW) sources and the LISA measurement process. Today, we use highly sophisticated models of the waveforms of GW sources that include realistic treatment of spin and harmonics, and that use extensive source populations derived, for example, from hierarchical merger models. Likewise, our description of the LISA measurement process is much more sophisticated [S-11, S-12], using realistic orbits of the individual LISA spacecraft and a full description of the combination of signals via Time Delay Interferometry (TDI). Rather than simply calculate SNR, we perform a complete calculation of parameter estimation with full co-variances, often involving 11 or more source parameters. The calculation of LISA science performance now requires the computing power of a large compute cluster.

Over the last decade we have also validated the algorithms used to analyze the LISA data by establishing the "Mock LISA Data Challenges" (MLDC), which have been very successful. (See [O-22] for a list of published papers and other references). In the MLDC, research groups from around the world develop algorithms and codes using a realistic LISA training data set consisting of both noise and known sources. All groups then "compete" on a challenge data set that contains a set of sources with an unknown set of parameters. As shown in Figure 7-1, the challenge data sets can be quite complex, including millions of simulated sources. A particular success of the MLDC has been the demonstration of analysis algorithms that have successfully identified ~20 thousand individual sources in the simulated LISA data stream (mostly galactic compact binaries) and correctly determined their parameters.

Scientific Advances. There have been many new developments over the last decade in areas of physics and astrophysics that can be studied with LISA. For instance:

- The co-evolution of galaxies and their massive black holes is now a major area of research. The energy release of massive black holes is recognized as a key ingredient of galaxy evolution and likewise the merger of galaxies is recognized as critical to the growth of central massive black holes.
- Driven by high angular resolution observations of our own galactic center as well as observations of hyper-velocity stars and extragalactic stellar disruption events, the dense stellar cluster in the centers of normal galaxies are now seen as fascinating, highly dynamic environments.
- Recent breakthroughs in numerical relativity have for the first time allowed accurate calculations of the final stages of black hole merger and ring-down, leading to a much better understanding of both the late-time waveforms for GW emission and the role of kicks and recoils in the post-merger event.

A full discussion of the scientific advances in GW astronomy since the AANM decadal review is beyond the scope of this response. Many of the advances are discussed in more detail in the papers submitted to the Astro2010 science frontier panels.

7.2. Technical Implementation

The LISA measurement concept and the top-level performance requirements are largely unchanged since 1997.

After NASA and ESA formed the joint LISA Project Office in 2001, the Project began routine formulation and technology development. The most notable changes in the technical implementation prior to the BEPAC (ca 2006) were the conception and evolution of Time Delay Interferometry (TDI) and the introduction of arm-locking for the mitigation of laser frequency noise.

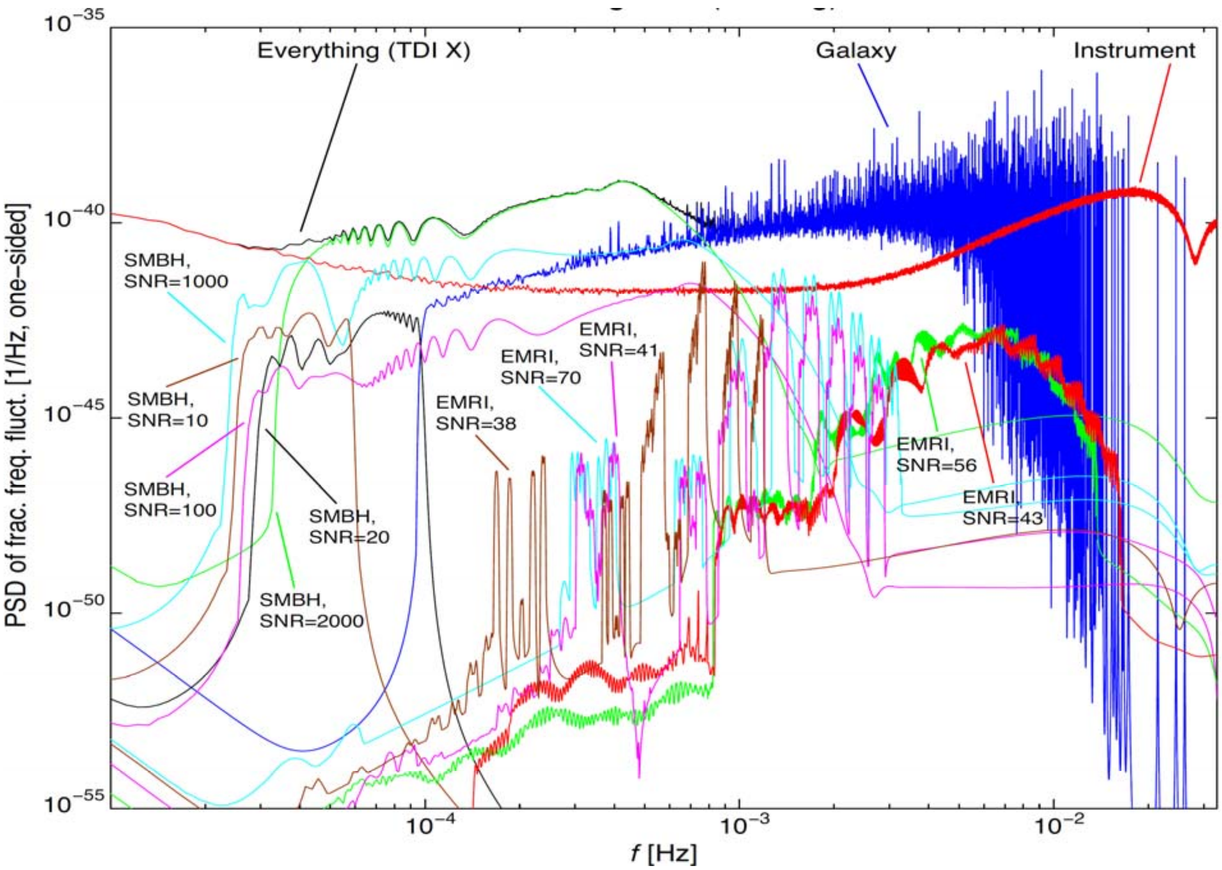


Figure 7-1. Mock LISA Data Challenge (MLDC) Simulated Data Set. Signal includes instrumental noise, 30 million galactic compact binaries, 5 massive black hole merger events, and 5 EMRIs.

The LISA Pathfinder (LPF) mission also started in late 2000, and NASA's contribution to LPF, the ST-7 Disturbance Reduction System, started not long after. By the time of BEPAC, both LPF and ST-7 were past their Preliminary Design Reviews, and considerable development had been accomplished. These activities advanced the development of the Gravitational Reference System (GRS), control laws, interferometers and micronewton thrusters to buildable designs, based on ground-tested prototypes. Since the BEPAC review, LISA Pathfinder has advanced past several major milestones:

- Subsystem CDRs and the system CDR are complete.
- Three microthruster technologies have completed ground-testing. The two technologies selected for inclusion on LPF have been selected. The flight model of one has been delivered.
- The ground testing of the GRS qualification model is complete. Flight models are in development. Delivery is expected in 2010 Q1.
- The qualification model of the interferometer is fully tested. The flight model is in development. The LPF interferometer is effectively the LISA short-arm interferometer.
- ST-7 has shipped its flight system to ESA for integration onto the LPF spacecraft. The drag-free control laws and colloidal micronewton thrusters are now flight-ready.

Since the BEPAC presentations (November, 2006 to April 2007), there have been many trade studies: off-axis vs on-axis telescope, one test mass per spacecraft with a backup test mass, in-field guidance and the elimination of moving optical assemblies, an alternate interferometry topology referred to as cross-strapping, elimination of the back-link fiber, angled sensing of the test mass vs polarization interferometry, fourth redundant spacecraft and much more. All of these studies reconfirmed the baseline with minor changes as the optimum design.

There are many technology development and risk-reduction activities going on in the U.S. and Europe. These activities have retired technical risk (e.g., variable sideband locking of laser stabilization cavity, laboratory demonstrations of TDI and arm-locking, microthrusters lifetime testing), and thereby advanced the technical implementation of LISA. The Project has also expended effort looking for economies in the architecture or cost-saving reductions in science scope. A summary of these efforts is provided in [S-3].

7.3. Estimated Cost

The AANM pre-dated the LISA Project Office by about two years, and pre-dated the NASA/ESA agreement on roles and responsibilities by five years. The LISA representatives to AANM – predating the Project – delivered a cost estimate of $425M in FY99 dollars. This estimate had many shortcomings: It was not a life-cycle estimate. Technology development was not included. A science program was not included. It was not based on any agreed-to allocation of responsibilities. It had very little contingency.

The first comprehensive parametric cost estimate was made by the LISA Project in May 2001. That costing was updated in 2003 for the Technology Readiness and Implementation Plan (TRIP) Review requested by NASA HQ. The TRIP Review included an independent costing that largely confirmed the Project estimate at the time. The parametric costing was updated an additional time for the BEPAC review in 2006-7, and again, an independent cost estimate was done. That independent estimate exceeded the Project estimate by about 50%, but there was insufficient explanation of the assumptions to allow a detailed comparison between estimates.

In the first half of 2009, as requested by NASA HQ, the LISA Project contracted with the Aerospace Corporation to obtain independent cost and schedule estimates. In this process: (1) the Project could supply the required information without time or page constraints; (2) the costing team could evaluate the technology readiness of all mission elements in greater detail than previous independent assessments; and (3) the Project team and the Aerospace team had a reconciliation discussion to identify differences in assumptions and understanding. The resulting Aerospace estimate of NASA's cost was 5% lower than the Project's estimate, and the schedule was 2% longer. Aerospace's TRLs were roughly the same as the Project's (see Table 2-1 in *Technical Implementation*). With the exception of the BEPAC independent estimate, all other estimates have been within 20% of each other for NASA's share.

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O-2. *LISA: Probing the Universe with Gravitational Waves*, LISA Project internal report number LISA-LIST-RP-436, v1.2 (March 2009).

O-3. *LISA Technology Status Summary*, LISA Project internal report number LISA-MSE-RP-0001 (2009).

O-4. *Overview of LISA Pathfinder*, LISA Project internal report number LISA-LPF-RP-0001 release 1.1 (April 2009).

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O-11. *Laser Interferometer Space Antenna (LISA) System Technical Budgets*, LISA Project internal report number LISA-MSE-BR-0001 (April 2009).

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O-20. *System and Technology Study Report*, LISA Study Team and Dornier Satellitensysteme GmbH, ESA-SCI(2000)11 (2000).

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S-3. R T Stebbins, *Classical and Quantum Gravity* **26**, 094014 (2009)

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S-5. Theodore H Sweetser 2005 *Class. Quantum Grav.* **22** S429-S435. Can be purchased at http://www.iop.org/EJ/abstract/0264-9381/22/10/039.

S-6. Eric H Cardiff and Gregory C Marr, *Proceedings of the 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 11-14 Jul. 2004, Fort Lauderdale, FL (2004). Preview at http://pdf.aiaa.org/preview/CDReadyMJPC2004_946/PV2004_3440.pdf.

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E-2. *Mission Analysis*, LISA-ASU-TN-4001

E-3. *LISA Pathfinder Experiments Master Plan*, S2-EST-PL-5007

E-4. *Constellation Acquisition Control for LISA*, LISA-ASD-TN-2003

APPENDIX A – Science Requirements and Requirements Flowdown

This appendix contains tables that are used in the flow-down from high-level science objectives to detailed allocation of noise budgets to LISA subsystems.

Table A-1 is a complete list of LISA Science Objectives and the corresponding Science Investigations. For each Science Investigation several Observation Requirements are defined, which are given in terms of observable quantities and the precision with which they must be measured. The complete list of Observation Requirements can be found in [O-7].

Table A-1. LISA Science Objectives and Supporting Science Investigations

Science Objectives	Science Investigations
Understand the formation and growth of massive black holes	Search for a population of seed black holes at early epochs Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs
Trace the growth and merger history of massive black holes and their host galaxies	Determine the relative importance of different black hole growth mechanisms as a function of redshift. Determine the merger history of $1x10^4$ to $3x10^5$ $M_{\odot}$ black holes before the era of the earliest known quasars ($z{\sim}6$). Determine the merger history of $3x10^5$ to $1x10^7$ $M_{\odot}$ black holes at later epochs ($z<6$).
Explore stellar populations and dynamics in galactic nuclei	Characterize the immediate environment of MBHs in $z<1$ galactic nuclei from EMRI capture signals. Study intermediate-mass black holes from their capture signals. Improve our understanding of stars and gas in the vicinity of Galactic black holes using coordinated gravitational and electromagnetic observations.
Survey compact stellar-mass binaries and study the structure of the Galaxy	Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground. Determine the spatial distribution of stellar mass binaries in the Milky Way and environs. Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations.
Confront General Relativity with observations	Detect gravitational waves directly and measure their properties precisely. Test whether the central massive objects in galactic nuclei are the black holes of General Relativity. Make precision tests of dynamical strong-field gravity.
Probe new physics and	Study cosmic expansion history, geometry and dark energy

Science Objectives	Science Investigations
cosmology with gravitational waves	using precise gravitationally calibrated distances in cases where redshifts are measured. Measure the spectrum of, or set bounds on, cosmological backgrounds. Search for GW bursts from “cusps” on cosmic (super-)strings.
Search for unforeseen GW sources	Strong signals will stand up above the noise. Weaker signals from some unexpected will be sought using a variety of methods, including wavelet transforms and/or coincidences with EM events.

Table A-2 provides the details of the Principal Science Requirements. These requirements are derived from the ensemble of individual Observation Requirements. The Principal Science Requirements can be summarized in just five numbers:

- Measurement band: 0.03-100 mHz
- Operational lifetime: 5 yr
- Nominal arm length: 5 million km
- IMS displacement noise: 18 pm/√Hz
- DRS acceleration noise: 3 x 10^{-15} m/s^2 √Hz

The table gives the frequency dependence of the various noise terms, which is used to generate the LISA sensitivity curve of Figure 1-1. See [O-7] and [O-8] for additional details.

Table A-2. Principal Science Requirements

Quantity	**Requirement**
Strain amplitude spectral density	$\sqrt{S_h}(f) = (\sqrt{5}) \times (\frac{2}{\sqrt{3}}) \times T(f) \times \frac{\sqrt{S_{\delta x\_IMS}(f) + S_{\delta x\_DRS}(f)}}{L}$ where T(f) is a transfer function representing the LISA instrument response to a differential length change
Single link IMS displacement noise amplitude spectral density	$\sqrt{S_{\delta x\_IMS}}(f) = \Delta X_0 \times 10^{-12} \frac{m}{\sqrt{Hz}} \times \sqrt{1 + \left(\frac{f_0}{f}\right)^4}$ with ΔX_0=18, f_0= 2 mHz)
DRS displacement noise amplitude spectral density	$\sqrt{S_{\delta x\_DRS}}(f) = 2 \frac{\sqrt{S_{\delta a\_DRS}}(f)}{(2\pi f)^2}$
Single proof mass DRS acceleration noise amplitude spectral density	$\sqrt{S_{\delta a\_DRS}}(f) = \Delta A_0 \times 10^{-16} \frac{m}{s^2 \sqrt{Hz}} \sqrt{1 + \left(\frac{f}{f_H}\right)^4} \sqrt{1 + \left(\frac{f_L}{f}\right)}$ with ΔA_0=30, f_H= 8 mHz, f_L= 0.1 mHz)
Measured Pathlength	$L = 5 \times 10^6 km$
Measurement Band	0.03-100 mHz
Operational lifetime	5 years

Table A-3 provides a flow-down of the noise budget to individual subsystems of the IMS, starting with the overall IMS displacement noise of 18 pm/√Hz. See [O-8] for additional details.

Table A-3. Summary of IMS Subsystem Noise Allocations

	$\times 10^{-12} \frac{m}{\sqrt{Hz}} \sqrt{1+\left(\frac{2\,mHz}{f}\right)^{4}}$		
Effect	**Total per group**	**Sub - Allocation**	**Comments**
Total IMS Error/Noise Budget	**12.0**		
Total of subsystem allocations	**11.7**		RSS of subsystems
Subsystem Allocations			
Shot noise	**7.7**		100 pW received power
Pathlength noise	**7.0**		root sum of squares
Pointing Errors		5.3	
Telescope pathlength stability		1	
Optical bench pathlength stability		4.5	
Measurement noise	**5.4**		root sum of squares
Photoreceiver errors		3	
Residual laser frequency noise		2	
Residual clock frequency noise		3	
Phasemeter noise		1	
Intensity noise		1	
Phase reconstruction		1	
Stray light		2	

Table A-4 provides a flow-down of the DRS noise budget to individual components arising in the instrument and S/C, starting with the overall DRS acceleration noise of 3 x 10(-15) m/s^2 √Hz. See [O-8] for additional details.

Table A-4. Summary of DRS Subsystem Noise Allocations

	$\times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1+\left(\frac{f}{8\ mHz}\right)^4} \sqrt{1+\left(\frac{0.1 mHz}{f}\right)}$		
Effect	**Total per group**	**Per group**	**Comments**
Total Acceleration Noise Budget	**30.0**		
Total of subsystem allocations	**19.5**		RSS of sub-allocations
Disturbance Groups			
Electrostatics		12.0	
Brownian		9.1	
Spacecraft magnetic		7.0	
Spacecraft coupling		6.0	
Spacecraft cross coupling		4.5	
Thermal		4.0	
Interplanetary Magnetic		4.0	
Misc small effects		4.0	

APPENDIX B - LISA Concept, Feasibility and Definition Studies

References made in the main document are found, with their codes, in the *References* section before the Appendices. This appendix is the full response to Question #8 in the *Payload* subsection of the *Technical Implementation* section.

Documents on the Project web site (lisa.gsfc.nasa.gov):

- *Laser Interferometer Space Antenna (LISA) Mission Concept*, LISA Project internal report number LISA-PRJ-RP-0001 (May 2009).
- *LISA: Probing the Universe with Gravitational Waves*, LISA Project internal report number LISA-LIST-RP-436 (March 2009).
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- J. Faller, P. Bender, J. Hall, D. Hils, M. Vincent, *Space antenna for gravitational wave astronomy*, in: Colloquium on Kilometric Optical Arrays in Space, ESA-SP 226 (1985)

This paper sums up the earlier studies regarding gravitational wave detection in space and is considered as the first concept of LISA

- *LISA – Proposal for a Laser-Interferometric Gravitational Wave Detector in Space,* MPQ 177, May 1993
- *LISA - Laser Interferometer Space Antenna for Gravitational Wave Measurements: ESA Assessment Study Report*, ESA SCI(94)6, 1994

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The pre-phase A study ran from 1994 to 1998 and was conducted by the LISA Study Team and supported by ESA

- *LISA Mission Concept Study*, Team-X study, JPL Publication 97-16, March 1998

This document summarizes the results of a study conducted by JPL's Team X in January 1997.

- *Final Technical Report Phase A Study*, Dornier Satellitensysteme GmbH, Matra Marconi Space, Alenia Aerospazio, ESTEC Contract no. 13631/99/NL/MS, 2000

The Phase-A study ran from 1998 to 2000 and was conducted by industry. This is the industrial report on the study

- *System and Technology Study Report*, LISA Study Team and Dornier Satellitensysteme GmbH, ESA-SCI(2000)11, 2000, http://www.srl.caltech.edu/lisa/documents/sts_1.05.pdf

The System and Technology Study Report covers the results of the Phase-A study and is jointly authored by the Study Team and Dornier Satellitensysteme. It contains most o the material that is in the Final Technical Report.

Space Technology 7 (ST7) Disturbance Reduction System:

- John K. Ziemer, Thomas M. Randolph, Garth W. Franklin, Vlad Hruby, Douglas Spence, Nathaniel Demmons, Thomas Roy, Eric Ehrbar, Jurg Zwahlen, Roy Martin, and William Connolly, *Delivery of Colloid Micro-Newton Thrusters for the Space Technology 7 Mission, /44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2008-4826*

This paper describes the colloid micronewton thrusters delivered to ESA as part of NASA's ST-7 instrument package for LISA Pathfinder.

LISA Pathfinder and its ESA precursors with relevance to LISA:

- *ELITE Technology Demonstrator for Multi-Satellite Interferometry Missions,* ESA-RSSD Proposal for SMART-2, October 1998

This document is a proposal for a technology demonstration of drag-free control and spaceborne interferometry

- *LISA technology package on board SMART-2,* Final Technical Report Release 1.3, ESA contract #15580/01/NL/HB, October 2002

This document gives a definition of the LISA Technology Package to be flown on board SMART-2

- *Science Requirements and Top-level Architecture Definition for the LISA Technology Package (LTP) on Board LISA Pathfinder (SMART-2).* LTPA-UTN-ScRD-Iss003-Rev1

This document describes the Science Requirements for the LISA Technology Package (LTP). It also gives a summary description of the LTP architecture.

- *LPF Experiments Master Plan,* S2-EST-PL-5007, Issue 1.0

This document provides a top-level, self-contained textual description, and schedule, of the experiments, and associated runs, to be performed during the nominal operational phase of the LISA Pathfinder (SMART-2) mission.

- *LTP System Design Synthesis,* S2-ASD-RP-3009, Issue 1.0

This document gives a comprehensive overview on the LTP System design. It is based on several precursor and requirement documents on the one hand. On the other hand this report is reflecting the investigations about the architecture of the LTP design that guarantees fulfilling the requirements of the customer as defined in the LTP Implementation Phase ITT. It comprises as well a synthesis of the design of the assemblies and units of LTP and as such provides an overview on the detailed functionality of LTP.

- *LISA Pathfinder System Design Synthesis Report*, S2-ASU-RP-2003

The LISA Pathfinder (LPF) System Design Synthesis Report describes the overall design of the LPF mission, details its constituent systems and elements, and summarises the key budgets.

- *LISA Pathfinder Mission Design Report,* S2-ASU-RP-5017, Issue 1.0

This document contains the following elements:

  - Introduction to Mission Design Concept – A brief summary of the mission design that resulted from the earlier study work to give a context to the more detailed analysis
  - Mission Design Requirements – A summary of the mission requirements that influence the mission design
  - Detailed Mission Analysis – Detailed design and analysis for the LEOP, transfer and operational phases of the mission

ESA's Formulation Study contractor, EADS Astrium GmbH has been produced many concept, feasibility and trade study documents in the five years of Formulation now past.

Note that these documents are considered competition sensitive and are generally <u>not</u> available without a signed Non-Disclosure Agreement.

System and Mission

- *Mission Design Description,* LISA-ASD-DD-5001

This document describes the overall design of the LISA mission. The main focus is on a description of the proposed design baseline as it is achieved at the time of the Mid-Term Review of the LISA Mission Formulation study. Therefore, several sections in this document are still TBD and will be completed during the second phase. In this context, only mission specific issues are described. Further design details can be found in the corresponding design descriptions and subsequent documents.

- *System Parameters and Error Budgets,* LISA-ASD-BR-5002

The first part of this document summarizes all parameters that are required in simulation models for the LISA mission. Such models are contained in the dynamic end-to-end simulation, the frequency cancellation simulation, the performance simulation, and for budget assumptions. Part two of this document gives a summary of the overall error budgets. These include pointing error budgets, acquisition budget, science performance budget (at all frequencies defined in science req.), alignment budgets, and calibration error budgets.

- *System Design Trade-Offs,* LISA-ASD-DD-5003

This document summarizes all design trades and decisions that have an impact on the overall LISA system design. Trades that only have a local effect as well as the more detailed analyses can be found in the corresponding design descriptions and supporting technical notes.

- *Product Tree,* LISA-ASD-PT-5001

This document represents the Product Tree for the LISA mission. The product tree includes all "products" that are required for the mission.

- *Requirement Breakdown,* LISA-ASD-TN-5001

This document describes the requirement breakdown from the LISA top level science requirement (strain sensitivity) to noise contributions from different elements of the mission. It mainly includes budgets for the optical path length noise and the acceleration disturbance noise. References to the original sources of the derivations and the technology data are included as well.

- *Coordinate Systems,* LISA-ASD-TN-5003

This document defines and describes all reference coordinate systems that are used in the framework of the LISA Mission.

- *Inputs to technology plan,* LISA-ASD-RP-5001

Based on the current status of the LISA Formulation Phase study all critical technical issues are listed, which need further investigations/developments in order to meet the LISA performance goals, to achieve a high system reliability compatible with the envisaged lifetime of 10 years, and to minimize the development risk and consequently to minimize the overall mission costs. In view of the needed extraordinary high measurement precision, the performance verification becomes a central issue for all technology developments. The related procedures and the eventually needed development of test equipment will also be addressed.

- *Failure Modes Effects and Criticality Analysis (FMECA),* LISA-ASU-DD-5002

This document provides a preliminary Failure Modes, Effects and Criticality analysis (FMECA) on LISA at system level. The coverage of the FMECA starts from the spacecraft composite separation from the launcher and analyses single point failures. FMECA is normally performed from a bottom-up approach. At this stage of the project (Mission Formulation Study) detailed information on the units is not available and the FMECA is performed with a top down approach.

- *System Budgets,* LISA-ASU-BR-5001

This document defines the technical budgets for the LISA Mission. The information contained within the main section of the document reflects the design at the time of the MTR. Budgets from initial comparative studies of design options are included in the appendix to provide perspective on the design process that has led to the current MTR design instance.

- *LISA Orbit Motion Revisited,* LISA-ASD-TN-2006
- *Operations and Operability,* LISA-ASU-TN-4010

This document describes the high-level preliminary operations and operability plan for the LISA mission, including the main mission phases and operations that will be performed, and the operations required for each of the elements on board the spacecraft.

- *Specification Tree,* LISA-ASD-PT-5002

This document provides an overview of the different levels of specifications, including mission, system element, subsystem, and equipment or software product.

- *System Design Specification,* LISA-ASD-RS-5001

This document specifies the high level requirements for the LISA system at the time of MDR.

- *General Design and Interface Requirements,* LISA-ASD-RS-5100

This document will eventually specify the general design and interface requirements for LISA. At this time the document is mainly in outline form, with just a few sections populated with requirements derived from current mission level requirements or from LISA Pathfinder.

- *Environmental Specification,* LISA-ASD-RS-5200

This document will eventually specify the environmental conditions for LISA. At this time the document is mainly in outline form, with just a few sections populated with requirements derived from current mission level requirements or from LISA Pathfinder.

- *Product Assurance Requirement Specification,* LISA-ASD-RS-5300

This document specifies the product assurance requirements applicable to the LISA mission. The LISA mission shall be designed, manufactured, and tested in compliance with these requirements, which are applicable to all suppliers of LISA hardware, software, and GSE.

Payload:

- *Payload Preliminary Design Description,* LISA-ASD-DD-3001

This document gives an overview of the current baseline configuration of the LISA payload, including the functional architecture, the mechanical layout, an overview of required actuators, the optical layout, the thermal and vacuum design. It does not include a breakdown of the science requirements, as well as an assessment of the science measurement performance.

- *Gaussian Optics Design Rules,* LISA-ASD-TN-3001

This document summarizes design rules for the optical part of the LISA payload (mainly the optical bench), which are derived from the requirement to minimize diffraction effects that might lead to a contrast reduction or measurement error on the acquisition photodiodes.

- *Opto-Mechanical Payload Design,* LISA-ASD-TN-3002

This document gives a detailed description of the opto-mechanical payload design for LISA, including the main measurement principles. The opto-mechanical part of the payload is the core of the LISA metrology system and consists of two movable optical assemblies per s/c, each comprising a Cassegrain telescope, a Zerodur® optical bench (OB), as well as an inertial sensor assembly as main elements.

- *Telescope Design and Trade-Off,* LISA-ASD-TN-3003

In this document we compile the various telescope types and layouts that have been considered during the first months of the LISA Mission Formulation study. The individual concepts are described by their optical layouts and comprehensive performance data such as image quality in terms of spot diagrams, wavefront errors and distortion as functions of field angles, etc. In a trade-off section, advantages and disadvantages of the presented concepts are discussed from which we derive a preferred concept and come to recommendations concerning telescope-material selection.

- *Optical Analysis with BeamWarrior*, LISA-ASD-TN-3004

This document describes results of optical analyses for LISA performed with the optics code BeamWarrior, a joint development of Astrium and ESO. The document is focused on the calculation of the far-field of a transmitted LISA laser beam, on the calculation of the heterodyne efficiency on the main quadrant photodiodes and on the intensity distribution incident on the CCDs

- *Point Ahead Angle correction*, LISA-ASD-TN-3005

This draft document describes PAA correction by actuation of an element in the optical path and located on the LISA OB. Main geometrical effects of an actuation and its impact to the science performance – in terms of piston (pivot projection) effects – are treated and requirements on an actuator are derived. An actuator for one DoF is sufficient. The required location of an PAA actuator on the OB in relation to pupil planes of telescope and detector optics was determined. Principal concepts – e.g. based on flexure mounted PZT – for actuators are given. First estimations on feasibility – in terms of tilt noise – by realization based on Piezo ceramics were performed. The technical development of a mechanism fulfilling the derived requirements is proposed.

- *Payload Mechanical Design*, LISA-ASD-TN-3006

The scope of this document is to describe the mechanical configuration baseline with all its components. First modal and structural analyses were performed to validate the design.

- *Laser system*, LISA-ASD-TN-3007

This document reviews the requirements for the laser systems aboard the LISA satellites and gives an overview of principal technological alternatives for their realization. As both the power stability and the frequency stability of typical free-running lasers will be insufficient for the purpose of LISA, the issue of power and frequency stabilization is addressed.

- *Vacuum Analysis*, LISA-ASD-TN-3008

This document provides information on the analysis of the achievable vacuum quality around the electrode housing. It is based on a more detailed analysis performed in the framework of LISA Pathfinder. In addition to the analysis results, design recommendations are given as well.

- *Payload Thermal Design*, LISA-ASD-TN-3009

The objective of this document is to describe the geometrical mathematical model (GMM) and the thermal mathematical model (TMM), based on the LISA payload design at MTR, and to provide the analysis results obtained.

- *Payload AIT*, LISA-ASD-TN-3010

This document describes the basic approach for the assembly, integration, and test of the LISA payload, consisting of the LISA Opto-Mechanical Core System (LOCS) and the LISA Interferometer Metrology and Avionics System (LIMAS).

- *Payload Mechanical Design & Analysis for MDR Baseline,* LISA-ASD-TN-3019

This document provides a detailed description of the Payload MDR Baseline Design established on the basis of accommodation and design trades performed together with mechanical analyses.

- *Thermal Design and Analysis for MDR Baseline,* LISA-ASD-TN-3020

This document provides a description of the geometrical mathematical model (GMM) and the thermal mathematical model (TMM) for the baseline LISA payload design with the MDR configuration.

- *Coupled Thermal Analysis for MDR Baseline,* LISA-ASD-TN-3021

This document provides a detailed description of the Payload MDR Baseline Design established on the basis of accommodation and design trades performed together with mechanical analyses.

- *Payload AIT - Test Level Definitions,* LISA-ASD-TN-3022
- *Payload AIT - Test Definition,* LISA-ASD-TN-3023
- *MOSA Harness Routing,* LISA-ASD-TN-3024
- *Technology Items for LISA Payload Config.,* LISA-ASD-RP-5005
- *Payload Design Requirement Specification,* LISA-ASD-RS-3001

This document specifies the requirements for the LISA payload. The necessary spacecraft parameters are considered as constraints and are listed in a dedicated section of assumptions, which can later be moved to an interface control document (ICD).

- *Payload-Spacecraft Interface Structure Design Req.,* LISA-ASD-RS-3002

Data and Data processing

- *LISA Science Data,* LISA-ASD-TN-1001

Discussion on science data sources and associated on-board treatment. Communication link and datation as well as clock synchronisation and arm length measurement is included. Excluded are technical housekeeping data.

- *LISA Measurement Performance,* LISA-ASD-TN-1002

Description of the performance model for the actual LISA baseline design; assessment of Baseline Design Measurement Performance.

- *LISA End to End Simulation,* LISA-ASD-TN-1003

Purpose of the proposed end to end simulation is to get a closer insight in the requirements arising from the need to overcome laser phase noise impact in the LISA measurement. In the traditional analysis the residual laser phase noise impact after application of TDI can be expressed as an equivalent error which can be compared against the shot noise as observable in a main-detector signal.

- *Signal Processing Chain,* LISA-ASD-TN-1004

Purpose of this document is to describe the characteristics of the detector signal defining the conditions and constraints for the phase meter operation. The properties of the detector signal depend on optical properties (stray light, power), modulation characteristics, and laser phase noise. The requirements guaranteeing the specified signal properties are also established in this TN.

- *Calibration,* LISA-ASD-TN-1005

This document the procedures for calibrating on orbit various housekeeping and ancillary metrology functions on the spacecraft.

- *Science Data Rate Estimation,* LISA-ASD-TN-1006

This document estimates the data rate transmitted to the ground, including requirements for dynamic range, accuracy, compression, and error-correction coding.

- *In Orbit Calibration Summary,* LISA-ASD-TN-1007

This document the procedures for calibrating on orbit various housekeeping and ancillary metrology functions on the spacecraft.

- *Phasemeter Consolidation,* LISA-ASD-TN-1008

This document discusses the issues related to the consolidation of the LISA phase measurement system functions, particularly at the system level, and the communication and embedding of these functions in the LISA payload.

- *E2E Simulator for LISA,* LISA-ASD-TN-2001

Description of the end-to-end LISA simulator, a design tool for performance evaluations. The simulator includes the equations of motion of the S/C, the environment, a thermal model, and active optical subsystem and control systems with actuators and sensors.

- *Payload Data Handling Specification,* LISA-ASD-RS-3A00

This document specifies the payload data handling, which is a software task.

Spacecraft and payload control

- *DFACS Design for LISA,* LISA-ASD-TN-2002

This document gives a mathematical description of the DFACS design on LISA. The design of the science mode control system is based on the experience gained with LISA Pathfinder. The same decoupling scheme is used and adapted to the LISA situation.

- *Constellation Acquisition Control for LISA,* LISA-ASD-TN-2003

This document gives a mathematical description of the Controller algorithm design on LISA during the constellation acquisition phase. The main focus is on the description of the guidance algorithm to be used during the acquisition phase. An overview is given on the underlying controller design as well, but details on this will be covered in a later document

- *Payload Control Systems,* LISA-ASD-TN-2004

This document gives a mathematical description of the payload control systems used within the LIST payload. The main focus is currently on the synchronization and the stabilization of the laser frequencies in section 3. This can be achieved by different means, e.g. a (tuneable) cavity and/or arm-locking. Different "levels" of arm-locking are discussed and it is shown that the overall arm-locking strategy proposed is stable in terms of the Nyquist criterion when the controller is properly designed.

- *DFACS Design for Two Active Proof Masses,* LISA-ASD-TN-2008

This document gives a mathematical description of the drag free and attitude control system (DFACS) control system design for the science mode for a LISA sciencecraft with the baseline two proof mass configuration. The control system design is based on the experience and design of LISA Pathfinder adapted to the LISA configuration.

- *AOCS Subsystem Design,* LISA-ASU-TN-4007

This document summarizes the functionalities and current architectural designs of the data handling system and the attitude and orbit control system for the LISA Mission Formulation study.

- *DFACS Requirement Specification,* LISA-ASD-RS-3900

This document specifies the requirements for the LISA Drag-free and Attitude Control System (DFACS). It includes the necessary spacecraft, optical metrology, and GRS parameters as constraints, listed in a dedicated section of assumptions that can be moved to an interface control document at a later time, although in a traditional control system these would be derived requirements.

Spacecraft and propulsion module design

- *FEEPs Accommodation and Configuration Trade Study,* LISA-ASU-BR-4004

This document describes the trade studies performed for the configuration and the accommodation of the FEEP on the LISA S/C

- *Spacecraft preliminary design description,* LISA-ASU-DD-4001

This document initially describes the trade studies performed during the LISA science spacecraft (S/C) design, and then describes the configuration status of the S/C design at the time of the LISA Mission formulation Study MTR.

- *Propulsion Module preliminary design description,* LISA-ASU-DD-4002

This document initially describes the trade studies performed during the LISA propulsion module (PM) design, and then describes the configuration status of the PM design at the time of the LISA Mission Formulation Study MTR.

- *Spacecraft Design Requirement Specification,* LISA-ASU-RS-4001

This document covers the top-level SC definition, the overall architecture, configuration and top-level functions, and the General Design and Interface Requirements. It specifies the detailed requirements specific to the SC subsystems, and addressed the generic and specific design requirements for space equipments and subsystems, details the environmental design requirements, and addresses the Integration and Test requirements, and outlines the Requirement verification control approach.

- *Propulsion Module Design Requirement Specification,* LISA-ASU-RS-4002

This document covers the top-level SC definition, the General Design and Interface Requirements, the environmental design requirements, the Integration and Test requirements, and outlines the Requirement verification control approach.

- *Mission Analysis,* LISA-ASU-TN-4001

This note describes the mission analysis activities performed for the LISA mission formulation study. The activities have been focussed in two areas. The first is the generation and optimisation of transfers to the target formation. These have been performed so as to both optimise the launch condition and the transfer manoeuvres, to maximise the mass of the spacecraft on station. Both high thrust, chemical propulsion based transfers and low thrust, electric propulsion based transfers have been generated. The second aspect is the analysis and optimisation of the LISA formation configuration. The objective is to design a configuration that reduces the sensitivity to third body gravity perturbations, such that relative position and range rate between the spacecraft experiences small variations. These aspects have been analysed parametrically to cover a range of scenarios.

- *Science Spacecraft/Propulsion Module Separation Analysis,* LISA-ASU-TN-4002

This technical note addresses the separation issues of the science spacecraft and its carrier for LISA Mission. It defines the safe nutation zones for the science spacecraft and its propulsion module after the separation, which is then used to determine the required spin rate for the composite spacecraft before separation given the separation impulses of the separation system. The derived constraint equations can also help determine the requirements on the separation impulses if the time to damp the spin rate of the science spacecraft is limited. Based on the analysis, the tasks and responsibilities for various subsystems (structure, propulsion, separation system, AOCS, etc.) involved in resolving the separation collision avoidance issues are identified.

- *Telecommunication system,* LISA-ASU-TN-4003

This document describes the design of the telecommunications system, including the antenna design, the operations schedule, and the contact schedule

- *Spacecraft and Propulsion Module AIT,* LISA-ASU-TN-4005

This document describes the first-draft overall model and AIV philosophy for the LISA mission SC and PM. This will attempt to take into account the peculiarities of the LISA mission, most importantly the duplication of spacecraft. An initial definition of the required test benches and GSE is also included.

- *Launch Vehicle Trade Off,* LISA-ASU-TN-4009

This document describes a trade study to determine the cost and programmatic impacts of alternative launch vehicles and scenarios for the LISA mission. The programmatic consequences of switching to a multiple launch option are evaluated, and a launch vehicle recommendation is made. Alternative launch vehicles to the previously considered Atlas V and Delta IV are identified, along with launchers able to perform individual LCM launches to both a direct injection and through apogee-raising manoeuvres, where we consider the switch to an LPF-style propulsion module. The document recommends the Atlas V Series 421 launcher as the baseline for the LISA mission. Accommodation of the LISA stack onto this launcher is then considered.

- *Thermal Analysis and Design,* LISA-ASU-TN-4011

This document describes the thermal control subsystem for the LISA Science Spacecraft and Propulsion Module. It includes the details of the thermal control hardware used and the thermal design solutions chosen, as well as an assessment of the critically important temperature stability of the payload interface.

- *LISA Thruster Configuration,* LISA-ASD-TN-2007
- *Vacuum Analysis for Propulsion Module,* LISA-ASU-TN-4006
- *Structural Analysis,* LISA-ASU-TN-4012

Results from a finite element model (FEM) and structural analysis of the LISA launch stack, spacecraft, and propagation module.

- *Radiation Analysis,* LISA-ASU-TN-4013
- *Constellation Control Consequences,* LISA-ASU-TN-4014
- *Payload Configuration Impact on Launch Stack,* LISA-ASU-TN-4015

This document assess the impact of various alternative LISA payload options on the overall LISA launch stack, including launch mass budget, overall dimensions, and a preliminary assessment of the natural frequencies.

- *LISA Alternative Launch Configuration,* LISA-ASU-TN-4016

This document presents a preliminary high-level analysis of an alternative to the baseline LISA launch stack configuration (the so-called "tuna-can" design) that attempts to address some of the deficiencies, including the lack of an overall mass optimization, the inaccessibility of the SC/PM separation interface, the necessary duplication of some hardware, and a problematic electrical interface with the launch vehicle.

- *Spacecraft Design Requirement Specification,* LISA-ASU-RS-4001

This document specifies the payload data handling, which is a software task.

- *Specification Template,* LISA-ASD-RS-5000

This document specifies the requirements of the LISA spacecraft design down to the subsystem level (level 3). The document has been prepared to keep the option open of outsourcing the S/C to a dedicated supplier. It is anticipated that future versions will have the subsystem specifications removed from this document and issued as separate specifications.

Subsystem Design:

- *OATM Force Noise,* LISA-ASD-TN-2009
- *OATM Analysis and Modeling,* LISA-ASD-TN-2010
- *Arm-Locking Performance Analysis,* LISA-ASD-TN-2011
- *Straylight Analysis for Cassegrain Telescope,* LISA-ASD-TN-3012

This document provides an analytical assessment of the stray light issues for the LISA telescope baseline architecture with a nominal Cassegrain-style design.

- *Telescope Refocusing - Optical Design,* LISA-ASD-TN-3025
- *LISA Command & Data Handling Subsystem,* LISA-ASU-TN-4017
- *Telecommunication Subsystem Design,* LISA-ASU-TN-4018
- *LISA Telescope Study,* LISA-TNO-TN-3001
- *Optical Bench Subsystem Specification,* LISA-ASD-RS-3100

This document specifies the requirements for the Optical Bench Subsystem for LISA.

- *Optical Assembly Subsystem Specification,* LISA-ASD-RS-3200

This document specifies the requirements for the LISA Optical Assembly Subsystem, which consists of the GRS, the optical bench, the telescope, and is articulated with respect to the spacecraft bus.

- *Telescope Subsystem Specification,* LISA-ASD-RS-3300

This document specifies the requirements for the Telescope Subsystem for LISA.

- *Laser Subsystem Specification,* LISA-ASD-RS-3400

This document specifies the requirements for the Laser Subsystem for LISA, including the master oscillator, phase modulator, power amplifier, and redundancy.

- *Phase Measurement Subsystem Specification,* LISA-ASD-RS-3500

This document is the first draft specification for the phase measurement subsystem, including requirements, assumptions, verification methods, and definitions.

- *Gravity Reference Sensor Subsystem Specification,* LISA-ASD-RS-3600

This document specifies the requirements for the LISA gravitational reference sensor subsystem, including all the necessary units and equipment to mechanically interface the sensor head to the optical bench. It also includes the optical interface, all the necessary electronics to operate the sensor, including the charge management of the proof mass, and the necessary harnesses.

Alternative Architecture Studies:

- *DFACS Design for Single Active Proof Mass,* LISA-ASD-TN-2005

This document gives a mathematical description of the drag free and attitude control system (DFACS) control system design for the science mode for a LISA sciencecraft with a single active proof mass instead of the baseline two proof masses. The control system design is based on the experience and design of LISA Pathfinder adapted to the LISA configuration.

- *Preliminary Payload Design Description/IFP Single GRS,* LISA-ASD-DD-3002

This document summarizes the design of an alternate configuration for a LISA sciencecraft based on a single active proof mass instead of the baseline two proof mass configuration.

- *LISA Payload Architectures with In-Field Pointing,* LISA-ASD-DD-3003

This document summarizes the design of an alternate configuration, In-Field Pointing, where the telescope and optical assembly on a scienceraft are kept fixed relative to the spacecraft bus, but changes in pointing of the optical axis relative to the distance spacecraft that occur during normal orbital motion are compensated with a large field of view telescope and an actuated mirror embedded in the telescope.

- *Telescope Design for In-Field Pointing,* LISA-ASD-TN-3011

This document summarizes the requirements for a telescope to follow the orbital motion of the sciencecraft with In-Field pointing instead of optical assembly articulation, and trades off several designs to arrive at a recommended configuration.

- *BeamWarrior Analysis for Off-Axis Telesocpe,* LISA-ASD-TN-3013

This document summarizes simulations of an off-axis, In-Field Pointing telescope, including the receive path and far-field phase distribution. Simulations are with BeamWarrior, a proprietary optical modelling code developed jointly by Astrium and ESO.

- *Mechanical Design & Analysis for IFP/Single GRS,* LISA-ASD-TN-3014

Summary of a the mechanical accommodation and design trades performed for the single active GRS with In-Field Pointing configuration, including a detailed description of two concepts that were investigated, the design features, and results of mechanical analyses.

- *Thermal Design & Analysis for IFP/Single GRS,* LISA-ASD-TN-3015

This document provides a description of the geometrical mathematical model (GMM) and the thermal mathematical model (TMM) for the LISA payload design for a single active GRS with In-Field Pointing configuration.

- *Mechanical Design & Analysis for IFP/Two GRS,* LISA-ASD-TN-3016

Summary of the mechanical accommodation and design trades together with supporting mechanical analyses performed for the two active GRS with In-Field Pointing configuration – the so-called PR-2 design.

- *Assessment of Payload Eigenfrequency and Launch Loads Requirements,* LISA-ASD-TN-3017

This document is a summary of an assessment of the requirements of the LISA payload with respect to the launch stack eigenfrequency and stiffness/load requirements.

- *Piston at Active Mirrors,* LISA-ASD-TN-3018
- *System Parameters and Error Budgets IFP,* LISA-ASD-BR-5003

The first part of this document summarizes all parameters that are required in simulation models for the LISA mission for an alternative configuration in which there is a single active proof mass, and In-Field Pointing of the telescope. Such models are contained in the dynamic end-to-end simulation, the frequency cancellation simulation, the performance simulation, and for budget assumptions. Part two of this document gives a summary of the overall error budgets. These include pointing error budgets, acquisition budget, science performance budget (at all frequencies defined in science req.), alignment budgets, and calibration error budgets.

- *Alternative Payload Concepts,* LISA-ASD-RP-5003

This document provides a first discussion of several different payload and mission alternatives in order to obtain a more detailed view of their individual feasibility, advantages, and drawbacks with respect to the baseline LISA concept.

- *Payload configuration trade-off,* LISA-ASD-RP-5004

This document contains the results of a formal trade study of five different payload configurations: the MTR design, a modified MTR design with an off-axis telescope, the PAR-1 configuration, the PAR-1b configuration, and the PAR-2 configuration.

- *Piston Metrology for the IFP Mechanism,* LISA-ASD-RP-5006
- *Requirement Breakdown IFP/Single GRS,* LISA-ASD-TN-5004

This document describes the requirement breakdown from the LISA top level science requirement (strain sensitivity) to noise contributions from different elements of the mission for an alternative configuration with In-Field Pointing and a single active GRS. It mainly includes the differences between this configuration and the MTR baseline design.

- *Requirement Breakdown IFP/Two GRS,* LISA-ASD-TN-5005

This document describes the requirement breakdown from the LISA top level science requirement (strain sensitivity) to noise contributions from different elements of the mission for an alternative configuration with In-Field Pointing and two active GRS. It mainly includes the differences between this configuration and the MTR baseline design.

- *SC and PM Design for IFOV Payload,* LISA-ASU-TN-4008

Previous review reports:

- TRIP Review 2003

This is the project's report for the Technology Readiness and Implementation Review, chartered by NASA HQ in 2003

- Technology Review (2005)

The technology review was chartered by NASA GSFC in 2005. This is the report of the review committee with responses from the project

Technology plans

- US Technology Development Plan 2005
- ESA Technology Development Plan 2005

These documents lay out the technology activities required for proceeding through the LISA project phases and to confirm the results of the Mission Formulation. The technology items to be developed for LISA are derived from the original technology plan and from the preliminary inputs from the Mission Formulation study.

Miscellaneous (Management, etc.)

- LISA Project Agreement Following the LISA meeting 11-12 August 2004.

This is the document governing the tentative agreement between NASA and ESA Headquarters on the allocation of roles and responsibilities in the LISA Project.

- Formulation Authorization Document, 1 October 2004

The officially document entering LISA into Formulation Phase.

- *LISA Independent Cost, Schedule and Technical Readiness Evaluation Assessment: HQ Briefing, Final Results w/ Action Items Incorporated.* The Aerospace Corporation, 3 June 2009.

The final presentation of results from the independent cost and schedule estimation by the Aerospace Corporation with final action items from the NASA HQ presentation incorporated.

APPENDIX C - BASIS OF COST ESTIMATE

Basis of Estimate - NASA Cost

The following sections document the processes and assumptions used in developing the cost estimates Basis of NASA Cost Estimate.

Mission Schedule

Detailed schedule presented in Section 5 was assumed for the grassroots costing exercise.

LIMAS

Cost estimate for this payload subsystem includes the technology development activities as well as the design and development of the flight units. The cost estimate also includes the integration of LIMAS with the LOCS subsystem as well as the support required during the system-level integration and test phase. Technical details of the LIMAS subsystem are documented in Reference O-5.

LOCS

LOCS, a scientific payload subsystem, is an ESA responsibility. The Gravity Reference Sensor (GRS), the major LOCS component, is being developed by ESA for LPF. The ESA cost estimate for LOCS is anchored to the development costs for LPF GRS and other LPF science payload elements. The NASA project did not attempt to estimate the grassroots cost of this subsystem.

Laser and Telescope subsystems provide simple and controllable interfaces within the LOCS subsystem. Therefore, if necessary, NASA can elect to develop these subsystems for delivery to and integration by ESA. For the Laser subsystem the NASA project chartered Lucent Technologies to estimate the cost of developing the flight-qualified lasers for the mission. For the telescope subsystem the project chartered the Goddard Space Flight Center's in-house Instrument Systems Development Facility to develop the cost estimate. Technical details of the LOCS subsystem are documented in Reference O-5.

Spacecraft Bus and Propulsion Module

The GSFC's internal Mission Development Lab was chartered to develop the cost estimate for the development and integration of the spacecraft bus as well as the Propulsion Module. This lab developed grassroots cost estimates for every bus subsystem as well as a parametric based cost estimate for the entire spacecraft bus. The higher of the two estimates were adopted as the NASA cost estimate for the spacecraft bus. The technical details for the spacecraft and propulsion module are documented in Reference O-6 and O-12.

Micronewton Thrusters

Cost estimate for the Colloidal Micronewton thrusters for LISA are anchored to the development cost of the thrusters for the LISA Path Finder. The thruster cost includes the design enhancements required to extend the lifetime of the LPF thrusters to meet LISA requirements.

Ground System & Mission Operations

This element includes the cost of the design and development of the LISA ground system as well as the cost of mission operations, based on the operations concept documented in Reference O-10.

Science Operations

The Science Operations cost estimate includes the cost for the mission science office, which is part of the LISA Project Office, and a science center that will be procured through competitive selection. The research grants program for the Guest Observer Program is NOT part of this element and is carried as a separate line item. Science Operations concept is documented in Reference O-9.

Mission Systems Engineering

Grassroots estimate for mission systems engineering was determined for two scenarios. For the scenario with NASA as the lead agency, this element assumed full responsibility of the mission systems engineering responsibilities with ESA in support role. In the scenario with ESA as the lead agency, the cost estimate assumes that besides supporting the systems engineering process, NASA will be responsible for independent analytical validation of the mission performance.

Integration, Verification and Testing

Grassroots cost estimate for this element was determined for two scenarios. For the scenario with ESA as the lead agency, NASA cost includes integration and verification of NASA provided elements and support for the system-level integration and verification of the NASA-provided elements.

Mission Management and Mission Assurance

These elements were calculated as a percentage of the total development and operations costs.

Launch Services

The cost for Launch services meeting LISA requirements was estimated by projecting today's costs to the LISA's launch readiness date.

Cost Estimates by Element

Table C-1 provides the cost estimates for each of the elements mentioned above. These costs were used to determine the total mission cost for the three scenarios.

Table C-1. Cost Estimates for LISA Mission Elements and Subsystems

Mission Element	**Element Costs**
Mission Systems Engineering	**$24,620**
LOCS Subsystems	$100,000
Telescope Subsystem	$50,000
Laser Subsystem	$50,000
LIMAS	**$78,143**
Sciencecraft (S/C)	**$265,468**
Attitude Control System (ACS)	$24,019
Avionics/C&DH System	$40,873
Flight S/W	$36,660
Power (incl. S/C Harness)	$36,110
Communication	$48,296
Mechanical	$30,406
Thermal	$12,725
GSE & Ground Segment	$4,460
S/C Bus I&T (incl. facilities cost & environmental testing)	$18,202
S/C Management & Sys Engr	$13,717
Systems I&T	**$23,602**
GSFC Sciencecraft I&T (incl. environmental test & propulsion module integration w S/C)	$12,250
System Level I&T	$8,370
Launch Stack Integration & Test	$681
Launch Site Operations (pre launch)	$310
LOCS-LIMAS I&T	$1,991
Prop Module (incl. facilities cost & environmental testing)	**$81,000**
Ground Segment	**$106,997**
NASA Mission Science	**$69,107**
3.1 Mission Science Office	$16,053
3.2 Science Center	$53,054
Guest Investigator Program	**$44,781**
Launch Vehicle	**$243,400**
Thrusters	**$85,000**

Appendix D - Acronyms

AANM	Astronomy and Astrophysics in the New Millennium
ACS	Attitude Control System
AM	Amplitude Modulation
ATLO	Assembly, Test, and Launch Operations
BEPAC	Beyond Einstein Program Assessment Committee
CBE	Current Best Estimate
C&DH	Control and Data Handling
CDR	Critical Design Review
CMNT	Colloid Micronewton Thrusters
CV	Cosmic Visions
DPR	Definition Phase Review
DRS	Disturbance Reduction System
DSN	Deep Space Network
EELV	Evolved Expendable Launch Vehicle
EM	Electromagnetic Engineering Model
EMRI	Extreme Mass Ratio Inspiral
EOL	End of Life
E&PO	Education and Public Outreach
ESA	European Space Agency
FEEP	Field Effect Electric Propulsion
FM	Frequency Modulation
FS	Flight Support
FTE	Full Time Equivalent
GB	Gigabyte
GI	Guest Investigator
GLAST	Gamma-Ray Large Area Space Telescope
GRACE	Gravity Recovery and Climate Experiment
GRS	Gravitational Reference Sensor
GS	Ground Segment
GSFC	Goddard Space Flight Center
GW	Gravitational Wave
HGA	High Gain Antenna
HZ	Hertz
ICD	Interface Control Document
IMBH	Intermediate Black Hole

IMS	Interferometry Measurement System
IPU	Instrument Processing Unit
I&T	Integration and Test
ITAR	International Traffic in Arms Regulations
ITAT	Integrated Technical Advisory Team
JPIP	Joint Project Implementation Plan
JPL	Jet Propulsion Laboratory
JPMO	Joint Project Managers Office
JWST	James Webb Space Telescope
LCC	Life Cycle Cost
LIMAS	LISA Instrument Metrology and Avionics System
LISA	Laser Interferometer Space Antenna
LISC	LISA International Science Community
LIST	LISA International Science Team
LOA	Letter of Agreement
LOCS	LISA Opto-Mechanical Core System
LPF	LISA Pathfinder
LRD	Launch Readiness Date
LS	Launch Support
LSST	Large Synoptic Survey Telescope
MBH	Massive Black Hole
MCRR	Mission Commissioning Results Review
MLDC	Mock LISA Data Challenge
MOC	Mission Operation Center
MOU	Memorandum of Understanding
MSE	Mission System Engineering
MSEAT	Mission System Engineering Advisory Team
MSEM	Mission System Engineering Manager
NASA	National Aeronautics and Space Administration
OA	Optical Assembly
OBC	On Board Computer
PA	Product Assurance
PAG	Particle Astrophysics and Gravitation (Program Prioritization Panel of Astro2010 Decadal Review)
PCDU	Power Control and Distribution Unit
PDR	Preliminary Design Review
P/M	Propulsion Module
PM	Proof Mass
PMS	Phase Measurement System
PSR	Pre Ship Review

QA	Quality Assurance
QPM	Quarterly Progress Meeting
RFI	Request for Information
RSS	Root Sum of Squares
SAIC	Science Applications International Corporation
S/C	Spacecraft
SDPS	Science Data Processing Segment
SIR	System Integration Review
SMBH	Super Massive Black Hole
SNR	Signal-Noise-Ratio
TAA	Technical Assistance Agreement
TB	Terabyte
TDI	Time Delay Interferometry
TIM	Technical Interchange Meeting
TRIP	Technology Readiness Implementation Plan
TRL	Technology Readiness Level
TWTA	Traveling Wave Tube Amplifier
U. S.	United States
USO	Ultra-Stable Oscillator
WBS	Work Breakdown Structure
WD	White Dwarf
WMAP	Wilkinson Microwave Anisotropy Probe