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DOCUMENT

L Class Internal Review Report

LISA Mission

Technical & Programmatic Report

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1 INTRODUCTION

The ESA Cosmic Vision 2015-2015 scientific programme foresees a down-selection process for the selection of one mission to become the first Large mission, or L1.

Three candidate missions undergo a technical assessment review that will be followed by a scientific review. Two of these candidates will be selected to enter the Definition phase, at the end of which one mission will be finally selected as L1.

Global objectives and proceedings for this review have been translated into a detailed implementation procedure, specific for each mission, that has been presented to the review team at the kick-off meeting.

The scope of this review encompasses technical and programmatic elements; a similar set of review objectives has been defined at each element of the LISA Mission:

- Mission
- LISA Composite Spacecraft (and Launch Stack)
- Propulsion Module
- Sciencecraft
- LISA Payload
- Spacecraft Bus (light review only with focus on interfaces, detailed review of Drag Free and Attitude Control system (DFACS))

For each of the above elements, the review team has examined requirements, architecture, design, feasibility, credibility, consistence and maturity.

The current technology status of the various mission components, together with their plan for further maturation has been assessed.

As concerns the international cooperation scheme, the LISA mission is foreseen to be implemented in cooperation with NASA. Several scenarios have been evaluated and discussed in detail at project level, at the moment no final cooperation agreement between ESA and NASA is in place.

One of these scenarios, called the “review working scenario”, has been used as a baseline for this review and it includes ESA being the mission lead and providing the integrated payload (with the phasemetre provided by NASA-JPL to ESA), integration activities of the payload onto the NASA-provided spacecraft bus, provision of the real-time test-bed and of the on-board drag free and attitude control system software (DFACS), provision of the propulsion modules and of the micro-propulsion systems and support to the NASA activities that include also launcher, spacecraft operations and part of the science data processing.

It has to be noted that in any of the alternative cooperation scenarios considered, the provision of the payload, considered the most demanding (critical) part of the mission, will be under ESA responsibility. As such the “review working scenario” covers all critical elements of the mission and allows to draw conclusions w.r.t. the overall mission feasibility.

Two available schedules, one provided by industry and the other by the project, have been analyzed and reviewed.

2 MAJOR FINDINGS – TECHNICAL MISSION LEVEL

The general mission design and presented overall configuration has been found by the board as being already at quite detailed level. A significant amount of trade offs and detailed studies have already been carried out for the LISA mission and lead to a solid mission design.

The baseline mission design is based on three identical composite spacecraft, each consisting of a propulsion module and a sciencecraft. During Launch the three composite spacecraft are stacked on top of each other and mounted in a stack configuration onto the launcher.

The general composite spacecraft physical design and overall configuration supports the mission requirements for launch, transfer to operational orbit, and science operations final orbit. Initial structural analyses show compliance with selected launcher environment, and show credible and acceptable mass budgets. It has been noted, however, that the nominal mass numbers are not always conservative, respectively consistent, e.g. for the battery sizing a value of 11.2 kg is quoted whereas a value of 7.8 kg is used in the system budgets. The 5 m^2 Solar Array of each sciencecraft is considered with a mass of 7.2 kg. This appears significantly underestimated. It appears that the mass of the clampband between the propulsion module and the sciencecraft is missing from the budget. While the overall effect of these un-clarities is small they need to be corrected. Globally the mass is found credible. Maturity contingency for the various units and a adequate system mass margin have globally been applied correctly.

Some concerns have been raised for the separation mechanisms. The separation mechanisms between the composite stack to the launcher and the composite spacecraft are based on existing design but, since not available at a diameter of 3.3 m, appear to be a dedicated development for LISA. While this not being a showstopper, the board was concerned on the timely availability of such dedicated development, including the necessary qualification activities. There was concern that these separation mechanisms may have impact on the overall mass (aside the cost and schedule implications).

The separation mechanisms between sciencecraft and the propulsion module have some heritage from small satellite applications, and are considered a possible solution for the required interface, especially as they require no access to the clampband interface during mounting. It appears, however, that they, similar to the clampbands between the composite spacecraft, equally require dedicated qualification for LISA. It is noted that if a more conventional clampband would be used at this interface, access to the clampband during integration would be very difficult and could lead to an increase of the height of the interface at the expense of additional overall mass. The board recommends to firm up the availability and need of qualification of the baseline clampbands in the next study phase.

As the separation between the sciencecraft and propulsion module constitutes a single point failure for the mission, the board has specifically assessed the separation analysis results. The design is supported by a stationary analysis with idealised assumptions made on the tip-off conditions and mass properties of both sciencecraft and propulsion module that shows compliance with the needs. However, to be able to finally conclude on the proposed separation strategy, the board recommends that a detailed separation transient analysis (normally only performed during the implementation phase) taking into account all the separation dynamics uncertainties is advanced and performed early in the next phase in order to ascertain that the required separation dynamics conditions are met with the proposed sciencecraft and “passive” propulsion module baseline design, including separation mechanism. One specific technical element of the propulsion module to sciencecraft separations is the impact of the connector separations on the dynamics. The quoted potentially high connection forces and the number of connectors used could become a driver to the separation. It is recommended by the board to pursue the ongoing design modification with a remote interface unit (RIU) to reduce the number of connectors between sciencecraft and propulsion module and to separate the connectors already prior to the actual separation activity.

The board notes that the present concept of the propulsion module is similar to the one used by LISA pathfinder, i.e. with a propulsion module without “intelligence”. While this being a valid concept the board saw room for potential improvement of the mission design by giving more functionality to the propulsion module. Due to the fact that the propulsion module cannot be re-used as such from LISA Pathfinder the trade-off on how to share tasks (and associated hardware) between sciencecraft and propulsion module should be re-opened in the next study phase. The benefits of assigning more tasks to the propulsion module during cruise and potentially after commissioning and the corresponding potential simplifications of the sciencecraft (allowing even more focus on the science in an undisturbed way) should be assessed. The assessment should include consideration of body-mounted solar panels onto the propulsion module, dedicated thermal control, the possibility to use the propulsion module(s) as data relay stations for the operational phase (and by that simplify the pointing and orbit maintenance for the sciencecraft, e.g. High Gain Antenna (HGA) re-pointing every 6 days) and costs and schedule.

The LISA requirement is to reach the target orbits within 14 months from launcher separation, whilst maximising the final injected mass into the target orbits.

The composite spacecraft stack is planned to be launched on an Atlas V 541 into a parking orbit. After a number of revolutions, the final launcher burn will manoeuvre the launch stack into an escape orbit. The composite spacecraft are then released from the launcher individually.

The Mission Analysis concludes on an optimised solution where, after leaving Earth's sphere of influence, each separate composite spacecraft begins the drift towards their final orbits. During the transfer, performing an out of plane manoeuvre, the required inclination for each of the three composite spacecraft will be reached. The required injection accuracies of 10 km and 10 m/s are considered achievable.

Optimisation of the Launch Composite transfers has allowed for less than 1000 m/s delta v per composite spacecraft to be generated for transfer durations constrained to 14 months, also allowing the launcher injection capability to be used in the most efficient manner.

It is to be noted that the Mission Analysis has been performed on a mass value of 5520 kg into escape orbit whereas the worst case mass as resulting from the system budget (with application of the system margin of 20 %) is 6155 kg (for a launcher capability of 6200 kg).

In the current analyses the spacecraft maintenance only accounts for high gain antenna re-pointing (once every 6 days) and recalibration. This leads to an operational availability far above the required 90%. In a future refined assessment other elements will need to be added including provision for contributing elements like safe modes with subsequent laser beam acquisition time (1 – 2 hours), Gravity Reference Sensor (GRS) DC Force/Torque Estimation (1 hour), Telescope Line of Sight calibration, point ahead angle mechanism and Telescope pointing direction calibration, phase slope estimation (for initial calibration and during operations), far field calibration, charge estimation and other calibrations for science (plus for non-science). A timeline (to be established in the future) for commissioning, science and maintenance modes would allow for confirmation of the 90% constellation availability for science mode, as requested in the Mission Requirements Document (MRD).

During the Launch and Early Operation Phase (LEOP), communication between the ground segment and the composite spacecraft will use conventional omnidirectional antennas to provide coverage for any spacecraft attitude. This will be provided by two low gain antennas (LGA) which are mounted on the outer shroud of the propulsion module. For the transfer phase, sustainable net downlink data rates (i.e. prior to packetisation or encoding) by this link, as a function of Earth – SC distance, are between 10 Gbps for LEOP down to 500 bps for on station.

For the communication on station using a high gain antenna the link budget is considered correctly established. Some assumptions used will need confirmation in the future. The design for the high gain antenna is still to be defined, as it is planned to be stowed in a limited volume between sciencecraft and propulsion module and have a proper visibility to Earth when deployed. Downlink is performed to a 34 m Deep Space antenna with 217.8 kbps at 8.43 GHz, the uplink with 2.2 kbps at 7.14 GHz (in the nominal case). On station emergency scenarios using the low gain antenna with 55 bps up- and downlink were also assessed.

The power budget was compiled based on consumption numbers from similar projects including LISA Pathfinder and a system margin of 25 % has been applied on all power estimates. This is not fully in line with the nominal power margin philosophy (maturity margin on equipment level between 5 % and 20 % plus a system margin of 20 %) to be applied for the early study phase. The only periods where the Solar Array cannot provide any/enough power are LEOP, short-duration off-pointing periods during transfer and the peak science mode. To meet power requirements during these periods, a Li-Ion battery pack (1300 Wh) is employed to cope with the power peaks (from 850 W available from the solar array to the max. 1090W). From the assessment of the solar array design and the available area on the sciencecraft it is concluded that adequate growth margin is available and should be used in the next phase.

The data budget is driven by a number of assumptions (e.g. the need to download the data collected from the whole constellation, via one sciencecraft, or total packaged data generation rate onboard one sciencecraft of 5kbps (11.0 kbps in System Budgets)). With these, a total amount of 2.592 Gbits of data is assumed. With a capability of 16 GB on each S/C, the data storage is not considered critical.

The board took that the nominal orbits of the LISA spacecraft are not indefinitely stable but get instable after a several years. The mission analysis shows that with careful selection of the initial orbit parameters one can achieve LISA spacecraft orbits that, with margin, do not require any maintenance for the nominal mission duration of 5 years.

The board noted that the leading specification is still the Mission Requirements Document (MRD – mission level) and not a System Requirement Document (SRD – space segment level) that is planned to become the main requirements document towards industry for the design of the satellite (this will also include the requirements on the standards to be used and the allowed tailoring). While the approach with a MRD only is normally fully adequate for a feasibility study phase and even into the definition phase it is considered not the best approach to the LISA mission. In view of the conceived ESA provision of the integrated payload industry has produced already a number of lower level specifications that will be linked to the SRD. While this is fully accepted and even necessary, the traceability of the requirements from mission level down to spacecraft design is difficult. The board expects/recommends that for LISA for the next phase a detailed SRD will become the leading requirement specification for the industrial study work.

3 MAJOR FINDINGS – TECHNICAL PROPULSION MODULE

The maturity of the propulsion module design is commensurate with a Phase 0 study, with a number of basic trade-offs performed (chemical versus electrical propulsion, monopropellant versus bipropellant, internal versus external cylindrical structure). It is noted that the conceptual design has been established on the basis of an earlier design configuration of the sciencecraft. The main difference to the present configuration is the mass of the sciencecraft. The up-scaling is considered an acceptable approach but need to be replaced by a full update in the next phase.

The propulsion module is of a relatively simple design including a supporting structure, propulsion subsystem units, electrical harness (the sciencecraft will provide all power, telecommand and control functions to the propulsion module), antennas, 2 star-trackers and a thermal control subsystem.

The total delta v requirement of 1139 m/s based on worst case composite spacecraft transfer delta v needs plus margins is available by the design.

As said above, the propulsion module trade-off studies were performed for a composite spacecraft mass of 1333 kg, stated to be scalable. Of specific criticality is the first axial Eigenfrequency that was 13 Hz for the stack mass of 4600 kg and dropped to 11.5 Hz for 5300 kg. For the present worst case launch stack mass of 6155 kg no calculation has been carried out and no result is available (requirement is > 8 Hz).

Conclusion:

The propulsion module design is very preliminary and based on an earlier mission design. The up-scaling is acceptable for an assessment study, however, it is recommended to perform a complete update in the next study phase.

4 MAJOR FINDINGS – TECHNICAL LISA PAYLOAD

The board has assessed the proposed constellation acquisition control strategy and associated acquisition error budgets. Assuming a fully validated end-to-end simulator and that the requirements on the calibration/alignment and stability error are met, the feasibility of the complete acquisition phase of the LISA constellation has been demonstrated with conservative assumptions on the attitude measurement system performances. The proof-of-concept of the acquisition control strategy is demonstrated with these tight (μrad level) calibration/alignment and long-term drift error budget assumptions that are not yet systematically justified and should be supported by analysis to be carried out in the next study phase. The Board further recommends that an independent validation of the LISA End-to-end simulator is performed before or at start of the implementation phase.

The LISA constellation acquisition strategy is very similar to the acquisition procedure of current space-based laser communication terminals. Due to different orbital conditions, though, the acquisition takes longer and will be based on the nominal sciencecraft positions provided by mission analysis and flight dynamics and will rely on the alignment of the optical system. The tight alignment requirements need to be maintained from the manufacturing of the LISA optical bench until its deployment in space. It is noted that full End-to-End alignment verification is not possible and relies on the sum of individual errors. The full feasibility of this approach needs to be demonstrated.

Alignment between two sciencecraft is performed by satellite attitude changes and point-ahead mechanism actuation. This leaves no room for the compensation of potential optical misalignments and is considered a risk issue by the Board.

It is noted that the drag-free-attitude-control-system (DFACS) design has reached a maturity level in the last years that do not require specific technology development from an algorithmic point of view. However, due to ground testing limitations, the DFACS performance is evaluated only on the basis and the assumption that the inertial sensor and the micro-propulsion system perform according to their design specification. The in-flight results of LISA Pathfinder form an essential part of the validation of the design, analysis models and associated assumptions of LISA Drag Free Reduction System (DRS) and DFACS designs, including validation tools for LISA drag-free control system and will therefore be required at the appropriate time.

The LISA optical metrology principle is based on time delay interferometry, which is a very sophisticated technique to remove interferometric measurement errors caused by laser frequency noise. The time delay interferometry and phase-measurement system concept is described in several documents and a technology development activity for the phase-measurement system is about to be started. In the LISA cooperation between ESA and NASA, the phase-measurement system will be developed by JPL. A demonstration breadboard has already been built JPL and measurement results exceeding the LISA requirements have been presented.

No major issues have been identified with the proposed LISA metrology system. The Board acknowledges the fact that this is covered by an independent validation that is part of the planned technology development activities.

Considering the high level of autonomy required at constellation and sciencecraft level, the Failure Detection, Isolation and Recovery (FDIR) is of critical importance. The board has reviewed the proposed multi-level FDIR concept which is unique to the LISA mission. In particular, a critical feature of the constellation level FDIR, based on a “graceful degradation” approach, is the number of operations for grabbing the proof-mass resulting from the fall-back to the sciencecraft safe mode level. As the required number of actuations for LISA Pathfinder is commensurate to the expected number of safe mode triggering and the LISA Pathfinder qualification models have shown no damage to the most critical components, there are no showstoppers foreseen with the proposed multi-level FDIR concept.

The board noted that different telescope optics have been analysed and traded-off at various stages of the study activities. The optical baseline design went through the following changes and evaluations chronologically:

- A telescope design trade-off in September 2005 concluded that a Korsch telescope was most adequate for an In-Field-Pointing architecture and a Cassegrain telescope would be best candidate for the On-Axis Operation concept. The Cassegrain system was subject of a coherent beam analysis and straylight analysis (see assessment below).
- In October 2007 an updated off-axis optical design with a fully reflective Schiefspiegler was analysed and baselined until September 2009.
- Finally the latest baseline was established following an optical tolerance analysis. The system consists of a off-axis Cassegrain optics with a refractive 3 element eyepiece. The analysis depth of this baseline is not yet at the level of previous baseline design but it is concluded to be feasible. Specific problems coming from the refractive elements in the design have not been addressed (relative index of refraction vs. absolute index of refraction, dn/dT, etc.).

The board confirms the feasibility and expected performance of the optical baseline design, however, recommends a further consolidation, including a consistent and complete analysis of this baseline design. This activity is partly being performed in the ongoing Optical Bench technology development study and is considered normal work for the next study phase.

The board noted that concerning the optics and in particular the telescopes sensitivity to the environment the most important issue is stability (required at the level of 1 pm). Alignment couplings with the phase centre offset of the telescopes are the dominant source of measurement errors. Jitter couples in particular via the lateral offset between the test mass centre of gravity and the phase centre of the telescopes. A detailed assessment of the effect was provided based on a simplified model of the interaction between optics and test mass.

The most sensitive part of the optics for aspects of stability is the spacer between primary and secondary mirror. This fact is well addressed in the documentation and therefore options for possible spacer materials are discussed (Carbon Fibre Reinforced Plastics (CFRP), Zerodur). However, both of these materials are dimensionally sensitive to the space environment:

- CFRP is thermally stable, but changes dimensions as a function of moisture release in space
- Long term dimensional stability behaviour of a specific CFRP material is not known, at least less knowledge compared to Zerodur could be assumed.
- Zerodur shrinks over time with a rate between 0.03..0.7*10^{-6} per year.
- Zerodur changes dimension as a function of radiation dose as well. This effect is very complicated and difficult to assess analytically as dimensional change is a function of radiation penetration depth.

It is considered that these dimensional changes can be predicted and/or compensated (focussing mechanism). As a consequence however, the phase centre offset will be subject of a long term drift during operation in space. This has to be calibrated in case it gets to large to comply with the required maximum measurement error (see below). The allocation of alignment budgets to the various contributors needs to be further elaborated in the next study phase.

The board noted that the proposed baseline optical design is an off-axis type optics. As a consequence dimensional changes of the telescope M1-M2 spacer will result in a lateral shift of the phase centre of the beam with respect to test mass centre of gravity. In addition to that the telescopes will suffer from a degradation of the wave front error due to a slowly increasing miss-alignment because of the dimensional changes of the M1-M2 spacer (and marginally the other components as well). Degradation of the wave front error of the TX telescope will scale directly the radiometric budget because the flux received by the receiver telescope will scale with the Strehl value of the TX telescope.

The proposed telescope design offers the possibility to refocus the telescope to correct the wave front error degradation (almost perfectly) to compensate this effect. Refocusing the telescope will most likely result in a phase centre offset change which will propagate directly in the measurement error. Impacts and consequences because of this effect have not been addressed. It is understood by the board that this effect can be compensated in orbit by a phase centre offset procedure; therefore it is not considered as a show stopper. However, it is considered that running through this procedure is a quite tedious and time consuming task with impact on the mission operations. This needs to be addressed.

As this phase centre offset procedure will be needed in any case, e.g. after refocusing of the telescope, it is not fully understood why extreme efforts for stability are considered for the M1-M2 spacer. From the analysis it can be seen that the noise level of the measurement is compliant with the specification if the phase centre offset is less than 0.25 mm. For the telescope M1-M2 spacer the phase centre offset due to lateral misalignment between M1 and M2 scales according to $\Delta PCO=\Delta M2*(M-1)$, with M being the secondary magnification of the telescope (about 10 for the proposed optics). This means that the secondary mirror lateral displacement can be up to 28μm until the level of compliance is reached. The board assumes that this can be easily achieved with a Zerodur or CFRP spacer. As long as thermal stability is provided this should not be a specific issue and can be provided with already established materials. The thermal expansion stability requirement put on the spacer material are understood to contain significant margin (at least two orders of magnitude). The review board recommends that the project revisits the origin of the requirement and relaxes the stability requirement in view of simplification of the design.

It was noted by the board that a stray light analysis was performed with the first baseline design (axial Cassegrain telescope). In the introduction of the straylight analysis document it is strongly recommended that the analysis shall repeated "before far reaching design decisions are undertaken" it is however not clear to the board if during the evaluation of the baseline design this recommendation was followed. At the time when the stray light analysis was performed the beam analysis was already known. According to the beam analysis 60% of the flux actually is emitted by the telescope while 40% must be somewhere in the system. The board would have expected that this potential stray light flux is analyzed, but only obscuration, spider, particles and Fresnel reflections have been analyzed (about 6.4% of the potential stray light flux).

With this major part missing in the analysis it cannot be positively concluded that the system design is correct with respect to stray light. This gap should be closed to remove the concern of potential implications in the system complexity for stray light control.

The LISA laser will require a specific development, however, it is expected to benefit from optical telecommunication NdYaG lasers, existing or under development (e.g. from TESAT), and providing a comparable output power. Key LISA requirements need to be demonstrated, including lifetime and phase stability, and a specific technology development activity is being implemented for that purpose. The architecture of the laser sub-system is baselined on a Master Oscillator - Power Amplifier configuration, a well-accepted approach to high-power laser design. The Master Oscillator operates at low power (few tens of mW) and is based on a Non Planar Ring Oscillator (NPRO) similar to the NPRO flown on TerraSAR-X or Aeolus. The Master Oscillator is followed by an Electro-Optical Modulator which modulates the phase of the beam and by a Fiber Amplifier which raises the output power of the laser to the required 2 W. The mode field diameter of the light propagating through such fiber (typical core diameter of 5 μm) leads to high optical power densities even for moderate power levels. The Fiber Amplifier end must be designed to avoid feedback reflectivity and withstand the high power density without damage.

The power density at fiber amplifier end termination is about 10 MW/cm2, exceeding the typical 1 MW/cm2 Laser Induced Damage Threshold (LIDT) for commercial Anti-Reflective coatings. However, this does not seem to be a problem; TESAT states a proprietary solution to this LIDT issue which is apparently well mastered by this company. The TESAT laser is qualified for 5 Watts and they have been performing life tests at 10 Watts (ongoing) for a total of 5000 hours.

Another element linked to high power density are the thermal lensing effect and the onset of non linear effects like Stimulated Brillouin Scattering (SBS) in the fiber. Proper thermal management will alleviate the lensing effect. The effects of SBS are increased differential phase noise and increased back reflection of the output power with increasing power density. The SBS issue is apparently dependent on the fiber manufacturing technology. IPG photonics demonstrated no SBS up to 5W output power while SBS was observed at 1.5 W on Nufern fibers. SBS is reduced by widening the laser line-width by phase modulation.

The Aeolus project observed the Laser Induced Contamination (LIC) for the operation of a UV laser in vacuum in the presence of outgassing products like silicon and hydrocarbons contained in non metallic materials (e.g. in adhesives).

The Laser Induced Contamination has equally been observed in sealed infrared (1064 nm) lasers purged with pure Nitrogen and operating above ambient temperature but with a lower contamination deposition rate than for the UV case. For LISA it is believed that this will not become a feasibility issue and this demonstration is expected from a technology activity, included in the TDA plan for LISA, on "Outgassing and Contamination characterisation for LISA", due to start in 2011. In the potential case of LIC above acceptable level when operating in vacuum, pressurisation (with partial pressure of Oxygen) for the optics prone to LIC would solve the issue but must be decided and implemented early in the payload development program to avoid later re-design.

The board noticed some inconsistencies in various documents concerning the (required) laser power. The given flux levels at various planes of the optical link between the transmitting and receiving telescopes were partly not in line with the required laser power as stated in the documentation. A simple worst case radiometric assessment leads to a laser power requirement which would be about 40% higher. It is however the board's opinion that the proposed laser concept holds sufficient potential to increase the laser power such that this point can not be considered as a show stopper.

The LISA payload contains, beyond those in the gravitational reference sensor (discussed below), seven mechanisms for which the status has been assessed as part of the review:

- LISA Point Ahead Angle Mechanism

  The definition status of the Point Ahead Angle Mechanism is quite advanced with two predevelopments performed that both have demonstrated that the main required technical performances for this mechanism can be achieved, i.e. the feasibility has been adequately demonstrated.

- Refocusing Mechanism

  A preliminary study has been performed for the refocusing mechanism. This refocusing mechanism is proposed to be based on an Attocube sliding actuator (COTS). Main criticalities for this Attocube actuator technology (relying on stick/slip motion) is the survivability under launch loads and lifetime capability under vacuum (specification is 40 times operations separated by long inactive phases), that has not been tested yet. There remains therefore a residual risk for the development of this mechanism and further activities with the aim of confirming the suitability of the specific mechanism design for LISA are recommended.

- Fiber Switching Unit

  A prototype of the fiber switching unit has been realized and was based on a customized ANR200 actuator (Rotary version of the linear Attocube). This prototype has performed well within the preliminary specifications (not fully consolidated yet). It has equally passed environmental (vibration, thermal cycling), non-sticking tests and lifetime tests including 20 actuations in vacuum where only 1 cycle is expected in flight. Motorization margin tests have also been performed and were successful. The nominal operation, following a long inactive phase in orbit (sensitivity to cold welding), still needs to be demonstrated. The risks associated to the development of this mechanism appear sufficiently mitigated.

- Optical Assembly Tracking System Drive Unit

  The level of definition of the Optical Assembly Tracking System drive unit is quite high already and good amount of information has been provided for review. The NEXLINE actuator has been selected after trade-off as translation stage motor for this mechanism. A mechanism has been designed for LISA Pathfinder, which is stated to be at TRL 4. For the actuator element of the mechanism a flight-qualified actuator has been shown to meet LISA performance requirements and is now at TRL 6. The Optical Assembly Tracking System Drive seems to be already under development in the US but ESA also plans a separate overall Optical Assembly Tracking System development activity in 2011. It can be concluded that, although the feasibility of this mechanism has not been fully demonstrated yet, some promising development and testing activity have already been performed on similar devices in the US. The risk concerning the development of this mechanism for LISA industrial phase could so far be considered correctly mitigated, although the criticality of this mechanism is considered very high and close monitoring of the development is recommended.

- Optical Assembly Tracking Mechanism hinge Launch Locks devices

  The information provided for the Launch Locks devices is stated to be protected, as the design is subject to a patent application. The proposed design seems based on standard technology; however, as the feasibility has not been demonstrated, there remains a residual but limited risk for the development of this mechanism for LISA implementation phase.

- Optical Assembly Tracking Mechanism Drive Unit Launch Locks devices

  The launch lock device will be mounted near to the OATM Drive Units. A sketch of this Launch lock is provided but the loads to be sustained are unknown. The actuator type to be used for the release of the launch lock has been proposed (G&H from US). The proposed design is based on standard technology, however, as the feasibility has not been demonstrated, there remains a residual risk for the development of this mechanism, and further activities with the aim of confirming the suitability of the specific mechanism design for LISA are recommended.

- Optical Assembly Tracking Mechanism Pivot

  While no technical information has been provided for review and consequently the feasibility of this mechanism is open, it is recognised that the complexity of it is not considered extremely high and a TDA that adequately mitigates the risk for the LISA implementation phase is not needed.

The gravitational reference sensor (GRS) as planned to be used for LISA is a straight rebuild of the sensor currently under development and qualification for the LISA Pathfinder (LPF) project. The board took note of the status and persisting difficulties of that development and the ongoing considerations for design updates and related additional development activities. While the qualification of the gravitational reference sensor for the LISA Pathfinder project has not been achieved yet, the completion of the build and qualification is expected in due time for the L-mission selection.

The board takes note of the status of the micro-propulsion system with the baseline micro-thrusters being the European Slit Caesium FEEP micro-thrusters, developed for LISA Pathfinder. As a backup, the American COLLOIDAL micro-thrusters are considered, equally been part of the LISA Pathfinder project. From the assessment the board noted that while most of the LPF performance requirements have been already demonstrated by both type of micro-thrusters, the capability to satisfy LISA total impulse and lifetime requirements has not yet been demonstrated. The total impulse and lifetime capability demonstrated as of today by the candidate micro-thrusters is still far from the LISA total impulse and lifetime requirements of 4.500 Ns and 40.000 hours: 520 Ns and 2.035 hours demonstrated for the FEEPs and 245 Ns and 3.478 hours demonstrated for the Colloidal thrusters.

The board acknowledges that the lifetime demonstration cannot be performed under “accelerated” conditions, i.e. ultimate lifetime demonstration will only be achieved with duration comparable with the mission duration. The LISA lifetime demonstration of the FEEPs, together with an upgrade of the micro-thrusters design that might be introduced as a result currently running component level tests are both planned to start after delivery of LISA Pathfinder thrusters flight units. It is noted that while the FEEPs are today still in the qualification testing for LISA Pathfinder, the Colloidal thrusters flight units have been already integrated into the LISA Pathfinder spacecraft and lifetime demonstration could start as early as 2012. It should be noted that the lifetime testing of 5 years as needed for LISA will, for both candidates, not be completed in time for the planned selection of the mission. This was considered acceptable assuming that the lifetime test had started and reached already a significant overall duration. In view of the criticality of the micro-thrusters for LISA, the board recommends that prior to start of the any design modifications of the micro-thrusters planned for LISA an independent review is called to confirm the proposed changes. Further, the board recommends in addition to secure the LISA mission by assessing the possibility to implement a further alternative micro-thrusters technology in parallel to the planned LISA lifetime demonstration activity.

The board noted that for both candidate LISA micro-thrusters the verification of the thrust noise, measured as part of the LISA Pathfinder activities, specially at low frequencies is dominated by the thrust balance background noise. The board acknowledges the fact that the use of the measured noise profile (thruster noise and background noise from thrust balance) for the LISA performance analysis leads to fully compliant performance. Consequently the board recommends to consider a relaxation of thrust noise requirements for LISA.

The board takes note of the limited estimated procurement time for the selected micro-propulsion system (3.5 years). Considering the need to procure in total a number of 72 FEEP thrusters for the LISA micro-propulsion baseline, the board recommends to consider alternative micro-thrusters configurations (keeping the redundancy approach) to reduce the number of thrusters that need to be procured.

The board was globally concerned about contamination and its impact on the science performance and has addressed this in some detail:

- The Vacuum enclosure of the Inertial Reference Sensor was assessed in detail in the frame of LISA Pathfinder and with a proper cleanliness and contamination control plan with dedicated steps showing that it can stay within the contamination budget.
- The contamination sensitivity of the telescopes is stated to be quite high and a cleanliness level considered of 0.5 x 10^{-6} gr/cm^2 (molecular layer of 5 nm thickness) with a goal of 0.1 x 10^{-6} gr/cm^2 (layer of 1 nm thickness).
- The possibility of contamination of the redundant FEEP cluster by the nominal one during firing as well as the whole contamination potential/hazard by the FEEP propulsion system has not been fully assessed during the previous Mission Formulation Phase. This is not considered to be critical if considered early in the design phase, i.e. it should considered in the more detailed design during the definition phase.

Considering the typical sources at composite spacecraft and sciencecraft level, i.e.

- CFRP telescope tubes
- MLI
- Cables
- Glue
- Propulsion subsystem of the propulsion module during transfer
- Micro-propulsion subsystem,

it is recommended to perform a dedicated contamination assessment in order to implement preventive means from the beginning in the design.

The technology development activities planned for the LISA mission have been discussed in the technical assessments above and have been found to be complete and to address the critical elements in a timely manner.

The board recommends in addition to the planned or running technology development activities to consider an additional backup technology for the micro-thrusters and to include a demonstrator of the refocusing mechanism.

5 MAJOR FINDINGS – PROGRAMMATIC ASPECTS

For the evaluation of the schedule and the development plan it has been generally assumed that the planned technology development activities for LISA are carried out according to plan and the critical technologies have reached TRL5 in time for the selection of the mission.

As concerns the technology demonstration that comes from the LISA Pathfinder project the board considered the in-flight demonstration as a pre-requisite to enter into implementation phase with LISA. In practice this means that the LISA Pathfinder spacecraft flight model spacecraft has been completed and all critical developments have successfully completed their qualification and acceptance testing and demonstrated their performance in line with the LISA needs. For the extension of the lifetime test of the FEEPs from the testing done on LISA Pathfinder to the LISA needs it was considered acceptable, with respect to the risk to the LISA mission, if the 5 years of lifetime testing had not been completed but had reached already a significant overall duration.

The overall development approach with a test campaign including a Structural and Thermal Model of the composite spacecraft and the launch stack is sound. Dedicated Engineering/Qualification Models are foreseen for the Payload. A real time test bench and further avionics verification benches are foreseen.

The systematic use of Proto-Flight-Models for the first sciencecraft should be re-assessed in favour of more extensive use of Engineering Qualification Models and then directly flight models.

The assessment of the schedules initially provided for the review was found specifically difficult due to the fact that the two schedules started on different assumptions. The schedule provided by industry assumed a start of the implementation phase 18 months earlier than the schedule of the project team, both leading to the same launch date. The industrial schedule concentrated on integration and testing activities and used generic boundary conditions for the start of the activities (see also detailed assessment below). The schedule provided by the LISA project was found globally in line with the boundary conditions, looked realistic but lacked the connection to the one provided by industry. The review board considered this mixed schedule input as not adequate to complete the assessment on the realism of the schedule (and the possibility to reach a launch date in 2020) and asked the project together with the industrial architect to rework completely the schedule, considering a number of the detailed comments made by the review team and the nominal boundary conditions for the L missions, i.e. start of phase B2 in the second quarter of 2014.

The updated schedule from industry has been received in due time for the completion of the review exercise. The observations and findings are summarized below.

The schedule includes a transitional phase A/B1 of one year duration. This is about correct (nominal start of A/B1 in early 2012 and completion of phase B1 by mid 2013). In addition to this nominal phase A/B1 a further phase B1+ of almost two years duration is considered necessary for detailed System and Technology consolidation activities and included in the schedule from mid-2012 until the kick off of phase B2. The phase B1+ activities are de-facto start of phase B (even if not at full speed) and will require significant effort and spending, including commitment to early procurements and start of technology critical manufacturing. The schedule shows start of phase B2 in February 2014, start of phase C in February 2015 and launch in December 2020, including six months of ESA margin.

The schedule shows a good optimisation of tasks, with identification of areas where parallel work can be performed in order to reduce the overall duration. The schedule is stated to be optimistic and success oriented (this is agreed by the review board) and includes some reduction and removal of critical tests (e.g. reduction of functional testing duration and removal of acoustic tests at FM level). The review board does not agree to all proposed de-scoping and considers that some of the removed FM system level test programme activities will have to be re-introduced. Assumptions are clearly defined on status of critical developments, however, the schedule assessment does not provide evidence that the planned implementation durations of these critical developments are realistic.

The schedule considers the baseline launch stack approach reviewed in this internal review. Another configuration is mentioned with a stack configuration with three individual S/C launched on, and from, a common interface adapter. This concept appears interesting and has claimed advantages in terms of overall mass and schedule robustness, however, has not been considered in this schedule assessment. Such fundamental issue should be addressed with priority as the implications are far reaching.

The presented duration, from start of phase B2 to launch, is just under 7 years, however, the de-facto presented project duration, from start of phase B1+ to launch, is 8.5 years.

Considering the input received, the assumptions made for the presentation of the schedule, having made its own assessment and considering the programmatic baseline approach for the L-mission selection with start of the implementation phase B2 in Q2 2014, the review board concluded that an implementation phase duration of about 8.5 years (including appropriate provision of contingencies) is a realistic target for the LISA mission.

This means that with start of phase B2 in Q2 2014 a launch in Q3 2022 is considered realistic.

The review board was addressing the question of the advantages of producing a fourth composite spacecraft as a full flight spare. This fourth spacecraft was considered to remain on ground and could be used as on-ground test bed but would be a flight spare ready for use in case of failure of one of the three flight model sciencecraft. While attractive at first glance the board concluded that due to the additional resources needed in case of use, the need of timeliness of this spare to be ready for science operations and the cost of an additional launcher, this option should not be further considered.

6 ACHIEVEMENT OF REVIEW OBJECTIVES

The major objectives as defined for the Review in the procedure are summarized below, together with the assessment of the board.

Technical feasibility of the LISA Mission

The proposed design of the mission has been assessed with emphasis to the ESA provided items as defined in the "review working scenario" that have been found to have reached already a quite mature status. The Board concluded that the technical baseline as presented is feasible.

Compatibility of overall development risk with the applicable schedule

The board considered from its own assessments that has been carried out for critical LISA payload elements that the overall development risk is compatible with an L-mission, i.e. the mission can be implemented with acceptable risk. The duration necessary for the implementation phase of the LISA mission is assessed to be about 8.5 years. With a nominal start of the implementation phase, start of phase B2, in the second quarter of 2014, a launch date in the third quarter of 2022 is realistic.

Compatibility of the estimated ESA cost at completion with the L-class mission budget allocation

This objective is addressed in Part B of this Report.

Completeness of the proposed technology developments

The development activities for the LISA mission are defined, address the critical technologies and, if started and conducted as planned, lead to technology readiness in time for the down selection for implementation. The board has identified and recommended a number of additional developments that should be introduced to further reduce the risk for the mission.

Assess the proposed cooperation plan

The proposed co-operation plan as defined in the "review working scenario" and the variants to it that are discussed are considered by the board to allow clear responsibilities and simple interfaces.

7 CONCLUSIONS AND RECOMMENDATIONS

The board has assessed the status of the definition of the LISA mission with emphasis on the ESA provided elements (as defined in the “review working scenario”) and found it at a quite mature and detailed level, fully adequate for a feasibility phase and ready to enter into definition phase.

The technology development activities have been identified and are in the technology development plan with completion dates in line with the nominal L mission down-selection in 2013. In view of the technical difficulties experienced in the past, the board has, in addition to the already established technology plan, recommended to identify and consider activities on a further alternative for the micro-propulsion system.

The board has given some recommendations and specific issues to be considered to be addressed with priority in the next study phase, i.e.

- Move from Mission Requirements Document to System Requirements Document
- Detailed assessment of the separation systems
- Update of the propulsion module design to the latest configuration
- Complete optical design and perform straylight analyses
- Perform a system level contamination assessment and prepare first control plan.

The board has evaluated to duration of the implementation phase and considers that with a nominal start of the implementation phase in the second quarter of 2014, a launch date in the third quarter of 2022 is realistic.

Finally the board would like to thank for the contributions and support to the review from the industrial teams and the ESA LISA team.