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DOCUMENT

L1 Mission Reformulation

NGO - New Gravitational wave Observer

Technical & programmatic review 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. The three L-candidates have undergone studies that have culminated in a review process completed at the beginning of 2011.

In early 2011, though, NASA declared that it could not commit on the implementation of a Large mission in cooperation with ESA for a launch in 2020. To take into account the changed international situation, in March 2011 the Executive decided to study European-only, or European-led, mission architectures that could recover a sufficient fraction of the science goals originally envisaged, with a target ESA CaC set at 850 M€. This new formulation of the LISA mission is called **N**ew **G**ravitational Wave **O**bserver (NGO).

The three L-candidates started then a reformulation exercise, with the basic underlying assumption that the work done in the previous years should enable a fast identification of technical possibilities, a preliminary technical reformulation and a clear identification of the related impacts on the science case.

This review, at the end of the reformulation exercise, is aimed to establishing the overall feasibility and credibility of the L1 mission candidate reformulated concepts – for both platform and payload - for a launch in 2022, and an ESA CaC of 850 M€ (e.c. 2010).

Concerning LISA, this new approach of a European-only mission implies substantial programmatic changes in the mission design approach with respect to the previous ESA-NASA LISA mission. In the previous configuration, ESA was providing the LISA scientific complement, that is the whole integrated and tested scientific instrument - based on the NASA provision of the phasemeter – and was integrating this onto the NASA-provided spacecraft bus in order to obtain three sciencecraft. Furthermore, ESA was to integrate the sciencecraft onto the ESA-provided propulsion module, before shipping the three composites back to the US for environmental verification and preparation for launch. NASA would then be responsible for the launch and for the mission operations, whilst the scientific operations would be conducted in a joint way with two mirrored science operation centres, one in the US and one in Europe.

With the change occurred in the spring of 2011, ESA had to design a mission that fits within the assigned financial envelope, whilst encompassing all elements, including those previously provided by NASA.

In addition to the change in the mission design, the procurement scheme of the scientific complement was also modified, by considering a Member States contribution for a well defined scientific instrument, to be provided by a Member States consortium.

For this exercise, a true European-only mission was designed that does not rely at all on non-European contributions. Should such contributions (from NASA or other sources) materialize in the future, they will be brought to fruition either by increasing the mission scientific return or by reducing the ESA investment in the mission.

2 REVIEW OBJECTIVES AND PROCEEDINGS

The global objectives and planning for this review are reported in the procedure memo SRE-PA/2011.080 issued on 31/08/2011.

This report has been drafted with contribution by all members of the review team and approved by the chairman. During the team meetings, the issues raised by the members were discussed with the LISA Projects. When more detailed discussions were required members of the review team contacted directly Industry and clarified the issues raised. There were no RID's produced, but the various items discussed have been recorded in an Excel sheet and reported as Annex A. After discussion and clarifications, some topics remained and were judged to be worth mentioning in this report. Only the potential issues have been reported here as technical findings and have been grouped into three sections: mission level, spacecraft bus (including propulsion module) and payload.

3 MAJOR TECHNICAL FINDINGS – MISSION LEVEL

The baseline mission design is based on three spacecraft in a V configuration - a Mother spacecraft with a full payload complement (i.e. two telescopes) at the "V" vertex and two Daughter spacecraft with only one telescope placed at the end of each arm of the "V". This reduces the configuration to two arms and four links, from the previous three arms and six links.

The arm-length has been reduced from 5 M km to 1 M km in order to simplify the payload design.

The launch scenario comprises 2 Soyuz-Fregat vehicles to launch the three satellites (M + 2 Ds) to (sub-) GTO from which they will proceed to the final orbital position with their own propulsion modules. An alternative launch scenario without substantial changes into the presented NGO configuration can be realised with one Ariane V launch carrying the three spacecraft. Another alternative, entailing a shared Ariane V launch carrying the three spacecraft was also presented by industry, but the design of the spacecraft would have to be dramatically modified and therefore it was not considered in this review.

The orbit is a slow-drift orbit starting from 10 degrees, with an orbital plane inclination of 60 degrees with respect to the ecliptic. The mission duration is 4 + 2 years.

Maximum reuse of units and boxes developed for LISA Pathfinder has been pursued, the propulsion module is a near-replica of the LPF one and the spacecraft bus and the propulsion module are identical for the Mother and the two Daughters. The spacecraft design can accommodate any of the three micropropulsion candidate systems (FEEPs, cold gas, mini-RITs), in volume, mass and power, offering the maximum flexibility.

The ground communication is planned for 8 hours every 48 hours, with individual downlink from each satellite. The HGA re-pointing can take place every two to six days, depending on the selected strategy.

The mission operations are performed by ESOC whilst the science operations scenario comprises ESAC for the initial scientific data processing and national centres funded by Member States for the detailed scientific data extraction and processing.

The current mission design is based on Member States contribution for a well-defined scientific instrument that comprises the optical bench with the attached gravitational reference sensor and detached phasemeter, to be delivered as an integrated and tested entity by a Member States consortium. For this stage of the study, the instrument has well defined requirements and interfaces and leverages the extensive experience acquired by Member States in the LISA Pathfinder project and their substantial investments thereby.

3.1 Conclusion

The NGO mission is based on substantial LISA Pathfinder heritage. Notably the propulsion module is a nearly recurrent item form LPF and the gravitation reference sensor is directly derived from the LPF Inertial Sensor Head. Moreover also the configuration and construction techniques of the science spacecraft is derived from LPF.

The new mission design with two shorter arms in a drifting Earth trailing orbit allows a simplification of the mission, which makes feasible a 2-launches with Soyuz Fregat. The possibility exists to use Ariane V in case the mass of the Daughter spacecraft will increase beyond the present good margins. No showstoppers have been found concerning the mission aspects.

4 MAJOR TECHNICAL FINDINGS – SPACECRAFT BUS

The spacecraft bus changes with respect to the previous LISA Mission Formulation (LMF) design are mainly concentrated in the mechanical and thermal configuration of the sciencecraft and in the propulsion module, as the electrical and data architecture remained fairly unchanged. Therefore these areas were scrutinised in some more detail, as reported in the sections below.

4.1 Thermal Control

This subject can be subdivided in four areas of interest:

- Optical Assembly Subsystem (OAS)
- Equipment mounted on lateral panels and spacecraft bays
- Upper platform floor
- Solar Arrays

4.1.1 Optical Assembly Subsystem (OAS)

The OAS can be insulated from the environment of the spacecraft bay by an MLI jacket and the panel inside the I/F ring can be used as a radiator surface. Given the limited dissipation produced inside the OAS, its temperature regulation should not present criticalities.

4.1.2 Equipment on lateral panels

Lateral panels of the spacecraft are used to accommodate P/L equipment and some platform units. Units are directly mounted on panels that can be used as radiators. The area available to radiators is quoted to be around 4 m2, which is enough for evacuating the total power of the spacecraft (c.a. 650 W). Therefore the temperature regulation of these units should not present criticalities.

4.1.3 Upper Platform Floor

The upper floor is used to accommodate platform units and communication units are mounted on the antenna panel.

Some of the platform units dissipate a high amount of power, like the PCDU (for which only 10.5W are quoted, but this figure needs to be justified because it appears too optimistic) and the OBC (for which 40W are quoted) without having a conductive heat path to radiators. Therefore, they are assumed to dissipate through the floor into the spacecraft bays and from there the heat is radiated to the radiators. The report assumes that a sink of 0°C is available from the spacecraft and this provides an average upper floor temperature of 24°C. This needs to be revised under more realistic assumptions, i.e.:

- the sink temperature would not be so low, but rather close to 20°C (this is the preferred level and the radiators will be trimmed to obtain that);
- the actual power density of the units will cause local overheating of the platform.

It needs to be clarified if local temperature and spatial gradients can be tolerated. In addition, if the floor will be made of CFRP, there will be a problem of compatibility due to different CTEs and local temperature of the units that needs to be addressed.

For the communication units, because of the high power and power density of the TWT, their accommodation needs to be clarified.

4.1.4 Solar Arrays

Solar array panels are predicted to run at different temperatures, with the hottest one at about 110°C and the coldest one at 47°C. It can be noted that there is a rather limited spread of the conversion efficiency values inferred from the data in the report (values ranging from 21% to 18.5%). Hence, it is recommended to provide a justification for the assumed temperatures and the assumed correspondent fall of efficiency to ensure that the expected power available is correctly evaluated[1].

4.2 Micro-propulsion

The spacecraft design is expected to accommodate a cold gas type of propulsion. One of the goals of the study is to verify that the spacecraft can accommodate the required propellant. Hence, it is necessary that the estimated quantity of propellant and its volume are correctly evaluated. The report concludes that 35.6 kg of propellant (GN2) need to be accommodated (actually 23.7 kg are computed, the difference being added as a margin). The propellant budget consists of one large entry (DFACS science operation) and others of much smaller entity. The largest share (22.8 kg w/o margin vs. a total of 23.7 kg) is computed by using a simulation facility that is derived from LMF and the result cannot be assessed in details. There are no reasons to doubt the LMF analysis, but due to the potential criticality in accommodating larger mass (or volume) of propellant, it is recommended to scrutinize once more the basic assumptions of this calculation in order to provide a higher confidence in the correctness of the result.

4.3 Structure & Spacecraft Architecture

As explained in the study report, the configuration of the spacecraft is constrained by:

- Small I/F ring of 800 mm dia. imposed by the re-use of the LPF Propulsion Module;
- Large Optical Assembly System (OAS) that needs to be placed in the centre of the spacecraft and that makes the implementation of a continuous central structure rather difficult;
- Large spacecraft outer diameter (c.a. 2400 mm dia.) dictated by the accommodation of

[1] As reported in the structure section, an increase of spacecraft dimension is seen as very critical. Therefore, it might be impossible to grow the solar arrays larger, should this be deemed necessary later in the design phase.

equipment and solar array dimensions.

4.3.1 Spacecraft Architecture

The resulting spacecraft structure carries large masses on a large diameter and the absence of a central cylinder prevents the possibility of transferring their inertia loads via shear panels. Consequently, loads generated on the periphery need to be transferred by bending and shear of a thick bottom plate. Axial loads (and ground transportation loads) are transferred to an upper cylinder and platform via struts arranged in three bipods. The envisaged load paths can be anticipated to be not very mass efficient and the design of involved interconnections will be a very important task. The envisaged architecture needs to be scrutinised and trade offs for improvement will be necessary. There might be an advantage to extend the lower interface ring through the lower floor to provide a stiff interface to the struts and the OAS brackets. Additional stiff connection between the ring and the lower floor need to be introduced. Other measures to brace the equipment panels need to be sought[2].

The masses on the large outer diameter and their indirect connection to the central part of the structure will result in axial and rocking (because of the large rotational inertias) modes that will be difficult to decouple from the PM modes if their frequency will not be high enough. In addition, it must be noted that, if the spacecraft modes are not decoupled from the PM ones, the overall stiffness of the composite will decrease from the values presented in the report.

Therefore, it is strongly recommended that the study of the resulting modes, the sensitivity to design options and coupled dynamic analysis with the PM be planned with a high priority as one of the first tasks of a phase B1. Requirements on the fundamental frequencies will have to be verified and introduction of relevant notches need to be evaluated and proven to be of acceptable entity. It must be also noted that the configuration does not offer an easy growth capability, because any increase of its outer diameter (should, e.g. larger solar array be needed or larger equipment need to be accommodated) would increase the rotational inertias and the inefficiency of the load paths.

4.3.2 Tank accommodation

The top platform does not provide necessary 'hard points' with clear load paths for supporting the tanks the way they are illustrated in the report. A supporting structure for the tanks with clear load paths to the main structure need to be assessed and its mass addressed. Probably more efficient layouts might be conceived by profiting of the presence of stiffening webs of the upper platform.

4.3.3 HGA accommodation and pointing

The HGA is assumed to be in its deployed configuration during launch. If, on one hand, this will avoid the use of a deployment mechanism, on the other hand it will introduce high amplifications that might make this configuration unpractical to implement. It was clarified that an existing design incorporating a bracing built-in structure will be used, which will have to be reviewed in the next phase.

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[2] This type of accommodation is usually resolved by using stiff 'shear' panels and a central cylinder that, as said, cannot be used in this case.

Another concern is that the HGA needs to be re-pointed every 2 or 4 days. Even though no mass figures or inertial disturbance is given for this mechanism, one would suspect that almost any movement would require electrostatic locking of the GRS proof mass, with consequent loss of science measurement. No analysis is given detailing the disturbance on measurement phase (time to lock down, unlock, waiting for PLM settling, reacquisition of RF lock).

4.3.4 Solar Arrays accommodation

The top part of the structure will provide 'hard points' for mounting the S/A panels. It is mentioned that common blades mounted on the upper platform web are envisaged to be used. Their implementation, mass and AIT implications will have to be addressed in the next phase, but it is expected to be similar to LISA Pathfinder.

4.3.5 Structural Mass

The present budget reflects the proposed configuration. The struts of the bipods with their end-fittings have the same design of the Propulsion Module ones. Some other elements are scaled from LPF. Adequate margins are applied. However, it cannot be excluded that the structure mass might increase due to the need of stiffening the load paths as discussed above. On the other hand the small total mass of the spacecraft mitigates this risk. Hence, once the structure design has been verified by the early B1 analyses, the concept design of the various parts and connections can be established and their mass evaluated.

It has also to be taken into account that the current mass is based on the use of the cold gas micropropulsion system with power system provisions for the other forms of electric propulsion systems. Should a different system be used (e.g. mini-RITs or FEEP), the mass saving per spacecraft would be substantial (>100kg dry).

4.4 Propulsion Module

The Propulsion Module is directly inherited from the LISA Pathfinder one. A minor reduction of the tanks size and adaptation of its axial length will be required for accommodation onto the launch vehicle. This will require some retesting but does not invalidate the general design. Indeed it will become more similar to the off-the-shelf Eurostar bus from which the LPF one was adapted.

A mechanical analysis included in the report shows that a PM of full length can carry the presently envisaged mass of the sciencecraft at the expected C.o.M. height.

It can be reasonably assumed that thermal control, structure design and propulsion design do not present critical issues being these aspects verified in the frame of LPF implementation programme. In fact, the required modification, which consists of shortening of the central cone to accommodate tanks of smaller capacity, leaves all the PM subsystems untouched. From a mechanical point of view, a shorter central structure with unmodified cross section properties, will obviously improve its stiffness and its fundamental frequencies. The design of the tank support struts will probably result oversized being the propellant load smaller than LPF, but this can be surely accepted and seen as an additional margin being the saving of the work for a new design and qualification a major asset for the programme.

The required tank capacity is derived from the propellant mass to be carried, which in turn is calculated from the Delta-V budget presented in the report. However, the conversion from Delta-V into propellant mass and the relative assumptions are not reported. Although one could imagine that established data and methods derived from LPF have been used, it would have been desirable for completeness and full traceability to have the calculations of the propellant mass available for review.

4.5 Assembly, Integration and Testing

The AIT models and tests are based on a rather classical philosophy and appear to be adequate for a proper qualification and acceptance of the three spacecraft. The many models entail a number of parallel activities whose feasibility depends on the industrial setup capability, both at ESA's Industrial consortium and national level that cannot be presently assessed.

Concerning the mechanical qualification of the NGO spacecraft, it is based on an STM of the mother spacecraft and on an STM of the mother Payload Optical Assembly. The STM of the spacecraft will be subjected to the mechanical environmental test campaign without its Propulsion Module (PM), i.e. not in its launch configuration. The report does not elaborate on this point, but it is assumed that the vibration test will be done with a test adapter sitting on the shaker table. Design will be then verified by a coupled dynamic analysis with the PM. This approach may be valid if dynamic coupling between the spacecraft and the PM can be excluded, otherwise the prediction of the resulting modes together with the definition of the notching profile will be quite un-reliable. This approach will also call for an unnecessary over-testing of the spacecraft structure, which might lead to an over-design of the spacecraft structure with consequent mass penalty.

It is recommended to critically revisit this approach with the aim of evaluating the advantages and risk reductions that a vibration test performed in its launch configuration (i.e. spacecraft mounted on its PM) will offer. It will be necessary to evaluate what would be the most efficient solution to procure the PM for this test among the possibilities of introducing of a PM structural model or of advancing the procurement of a PM PFM that will be re-used later for the PFM test campaign.

4.6 Conclusions

No major issues have been found in the Electrical and Data architecture. The Power subsystem, Data Handling and Communications are largely based on the previous LMF and their design appears adequate for this phase of the study.

The major issue identified are in the mechanical area and are connected with the architecture of the configuration that imposes the adoption of a non-efficient and unconventional structure design (spacecraft of large outer diameter with a small I/F ring). This is however also the same configuration used in LPF, though with important differences (e.g. shear panels). Therefore this issue cannot be classified as a 'show stopper' but it has to be addressed and answered with the highest priority at the start of phase B1.

The structure mass presently incorporates adequate margins to absorb a possible increase dictated by the need to stiffen the various parts and connections of the structure. This also needs to be addressed very early in a phase B1.

The re-use of the LPF PM should not present major issues, with the exclusion of the draw-back of interfacing the spacecraft through a small diameter ring as it is discussed above.

The mechanical verification will need to be re-evaluated to take into account the possible implications of dynamic couplings between spacecraft and PM.

5 MAJOR TECHNICAL FINDINGS – NGO PAYLOAD

The PL design has been inherited from the original LISA with some simplifications in addition to the simple removal of one interferometer arm. The general design concept based on a Michelson interferometer is maintained, but substantial changes are proposed for:

- the telescope which has smaller diameter and is proposed now completely in Zerodur
- the ancillary measurements (optical truss, PAAM metrology) that have been eliminated to reduce the number of phasemeter channels and to gain space for reducing the dimensions of the Optical Bench.
- The Point Ahead Angle Mechanism that has been removed
- the Optical Bench which has now less components mounted on it and a smaller dimension

5.1 Optical Bench

Following the diameter reduction of the telescope, the dimension of the OB is the driver for the P/L accommodation in the SC and therefore for the two NGO daughter spacecraft to fit in a single Soyuz. The new OB has shrunk considerably, allowing a considerable reduction in the P/L height. To make the new dimension possible however, an OB having components on both sides is proposed. This is not seen as a major problem, but the alignment of the optical components can be more difficult, there is a need of an optical periscope and the handling of the OB during manufacturing needs to be carefully planned. So the new OB even if smaller and less populated, is not considered as simpler, but requires some further detailed study.

5.2 Telescope

The telescope diameter has shrunk from 40 to 20 centimetres. This allows an “all Zerodur” design, as opposed to the previous telescope featuring Zerodur mirrors and a CFRP spacer, as realised in the SILEX telescope (25 cm diameter) with similar WFE requirements. This is seen as a considerable simplification. In fact, the original design of the 40 cm telescope had a spacer of about 60 cm designed to have a “zero matched CTE”. This means that the design was such that the thermal expansion of the CFRP spacer was compensated by an opposite thermal expansion of the joints and interfaces with the mirrors. To do this also a fairly accurate knowledge of the operative temperature was required. Moreover, the CFRP spacer was expected to outgas and shrink at the beginning of mission, so also that dimension was to be compensated for. The thermal expansion coefficient of the Zerodur instead is smaller than that of CFRP and so all these corrections are not required anymore. From the optical standpoint, the specification for the telescope performances is unchanged and so manufacturability of the mirrors is not seen as a problem. However the overall stability of an all-Zerodur telescope to the required level (picometer level within the measurement bandwith) considering aging and radiation environment has to be further investigated and confirmed, possibly by test[3], before the final selection of the technology is made.

[3] Measurements of the Zerodur OB performance at pm level have been successfully performed several times by LISA Pathfinder on a similar scale construction. However the tests were for a short duration (hours) in a thermal vacuum environment, but without radiations.

5.3 Ancillary measurements

The ancillary measurements were the “optical truss”, measuring to picometer accuracy the stability of the distance between primary and secondary mirror of the telescope and the Point Ahead Angle Mechanism (PAAM) optical readout, providing a microradiant readout of the Point Ahead angle. These ancillary measurements were not necessary to meet the pathlength error budget, but were meant to be diagnostic tools in case problems were occurring in flight. In the case of the optical truss, this was also used to confirm that the expected final dimension was reached in flight.

The elimination of the ancillary measurements therefore does not jeopardize the mission performances[4], but only the ability to debug the system in case of anomaly. The new telescope featuring an all Zerodur design, if it will be confirmed by the future more in-depth study, mitigates the potential risk of eliminating the optical truss. The elimination of these ancillary measurements allows a considerable reduction of the number of the Phasemeter channels in addition to save space on the Optical Bench.

5.4 Single Optical Assembly in the daughter SC

This allows a considerable reduction of hardware on the daughter SC, while maintaining the functionalities of the LISA system. The lack of the laser system on the “other arm” optical assembly has been overcome by using a local low power laser. This could be the NPRO used in LISA Pathfinder and it is not seen at all as a risk or problem.

5.5 Performance budget

The pathlength error budget has been maintained to 12 picometer for the single interferometer arm. This is considered sound. The acceleration noise budget also is maintained as per the original LISA requirement. This is also sound.

A non-compliance by a factor 3 for the telescope and spacecraft pointing stability is highlighted if cold gas thrusters are used as micropropulsion system. This non-compliance does not affect the overall acceleration noise requirement, which is sill met. Moreover, the noise figure used for the cold gas thrusters is judged to be too conservative and not in line with the actual test results of Gaia. If the DFACS analysis is confirmed, a re-shuffle for the error budget will have to be done to verify the actual impact of this larger pointing jitter.

5.6 Four-arm constellation

The new orbit, slowly drifting away from Earth, allows for a slightly smaller relative velocity between the spacecraft along their interferometry arm. This is an advantage for both the phasemeter design and the photodiodes. Both of them in fact have to provide sufficient dynamic range to cope with the beat note of the interferometer, which is changing linearly with the Doppler velocity.

The manoeuvres sequence of each spacecraft to establish the optical link between them (constellation acquisition) was considered in past reviews of the original LISA design as a critical

[4] the PAAM itself has been eliminated from the design thanks to the shorter arm length and the new telescope with reduced aperture.

mission phase. Extensive analyses and simulations were performed to prove the robustness of the proposed approach. For this mission re-design it is believed that this phase is much less critical because NGO has only four arms, however there is no comment or evaluation about this in the report.

5.7 Conclusion

The new PL design is conceptually the same as the previous LISA, but it is simplified in many aspects, mostly at the expense of a decreased diagnostic ability. It is still able to deliver the specified performances and no major criticalities have been identified.

The recent results of the LISA Pathfinder LTP, showing few picometer stability for the LPF interferometer and a GRS acceleration noise just a factor three away from the NGO requirement have also demonstrated the achievability of the overall performance budget.

6 TECHNOLOGY DEVELOPMENT STATUS

The review team has reviewed the status of the technology development as presented by the Study team in the document *LISA Technology status summary - LISA-EST-RP-890, issue 2, 1.11.2011.*

In general the technologies in NGO can be divided into two categories: those to be flight proven by the LISA Pathfinder mission, to be implemented in NGO with minor or no modifications and those technologies which are specific to NGO and hence have no precursors in LISA Pathfinder.

The Technology Readiness level, as judged by the Review team, is summarised below.

Technology	**Current TRL**	**Rationale**
Optical Subsystem	4	Optical system requires no new materials or techniques. The NGO optical bench uses the same process as the LISA Pathfinder bench (which is at TRL 6), which has demonstrated on ground in representative environment better than NGO requirements.
Laser Subsystem	4	Laser components for LPF and EDRS missions are at TRL 6, the TerraSAR-X system is at TRL 9, system level performance for NGO needs to be verified.
Laser Frequency Noise Suppression	5	Laser frequency noise suppression (TDI) verified in JPL testbeds. Pre-stabilization options verified in the laboratory.
Phase Measurement Subsystem	4-5	Previously expected to be provided by NASA, has reached TRL 5 at JPL. Breabdoards for NGO have been developed by AEI-Hannover and are at TRL 4. A technology activity is ongoing to mature this item to TRL 5 by end of 2012.
Gravitational Reference Sensor	4-6	LISA Pathfinder GRS flight hardware is available, with the exception of the launch lock mechanism which is currently at TRL4 (grabbing mechanism is instead at TRL 5).
Point Ahead Actuator	6	Two prototypes with different designs, implemented by two different industries, were successfully validated in relevant

		environment. This element is not required in the current design.
Optical Assembly Tracking Mechanism	4	A flight-qualified actuator has been shown to meet NGO performance requirements. The PAAM development has shown that the OATM is not critical and can be implemented. A technology development activity will start in 2012.
Micronewton Thrusters	5-6	The demonstration of micro-Newton thrusters is one of the LPF mission objectives. Possible options for LPF are FEEPs, cold gas and µRIT microthrusters. NGO will likely fly the same system selected by LPF. Only lifetime demonstration will be required.
OB Photodiodes	4-6	InGaAS PD have been tested in ground thermal vacuum environment by LPF (TRL 6). Si PD have been developed and are at TRL 4.

6.1 LISA Pathfinder Technologies

NGO is designed to be compatible with all micropropulsions systems considered by LPF. This makes the NGO implementation very robust with whichever LPF microprpulison system. However is should not be forgotten that the micropropulsion lifetime is presently demonstrated by LPF only for the LPF much sorter lifetime (600 Ns, in terms of total impulse). Since the required total impulse depends on the mission lifetime, but also on the propellant feeding system (common tanks or distributed) and on the thruster failure handling, it is not presently clear how much the lifetime of the LPF micropropulsion system will have to be extended. Nevertheless, given the capability of NGO to accommodate all three micropropulsion systems, the review team believes that the associated risks are limited and are manageable within the L1 implementation schedule.

The other LPF derived technologies (e.g. Optical bench, GRS Front End Electronics) requiring enhancements are well covered by technology developments.

There is probably one item, the laser photodiodes, both single and quad, that has given LPF some headache that would benefit from a dedicated development before NGO starts in Phase B2.

6.2 NGO Specific Technologies

All the NGO specific technologies appear to be well covered by existing development activities. In some cases the activities are said to be on-hold. It is especially recommended to put the right efforts in the development of the High Power Laser, even though it can be based on existing developments in order to measure the NGO required performance.

In general, in order to maintain the competence in industry and institutes where the LISA Pathfinder and LISA technologies are developed, it is recommended to advance technology procurement as soon as the development is completed and the L1 mission is selected.

7 MAJOR FINDINGS – PROGRAMMATIC ASPECTS

The schedule presented in the ASD document shows a total of 8 years from start of phase B2 until launch, but is very sketchy and cannot be analysed in detail. In general terms the review team could not find evident inconsistencies, but it is clearly loaded with many parallel activities. This is due to the development of many spacecraft, payloads and models to be carried out at the same time. It is impossible to assess the feasibility without an industrial and payload consortium concept. It has been made known to the review team that the assembly GRS/optical bench will be provided by Member States and a sort of verification will be performed by them before its integration with the telescope inside the sciencecraft. This is considered a feasible approach but requires a further detailed elaboration and agreement with Members States.

The mission based on two Soyuz launches assumes that the adaptor for the dual launch of the two daughters spacecraft will be qualified and provided by the launch service provider. This assumption needs to be verified before the start of the programme.

In conclusion, provided that the above points are addressed and properly solved, the review team could not find any show stopper in the schedule presented.

8 RISK ASSESSMENT

A thorough risk assessment has not been performed during the review. However the major risks identified and the associated mitigation actions have been collected in the table below. A Risk Index[5] assessment has also been preliminarily attempted.

Risk Index	**Risk**	**Mitigation**
D4	Complexity caused by multiple spacecraft development will impact schedule and cost	- System I&T will not be a serial process - Daughter S/C, P/L Optical Assemblies and Prop Modules will be identical, Mother S/C has differences in Optical Assembly - Appropriate margin and flexibility will be incorporated into the schedule - Will rely on ESA and industry past experience in developing multi-S/C programs (i.e. CLUSTER)
C4	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 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 validated by hardware testing in the lab - Experience from other space projects indicates that missing end-to-end test does not lead to

[5] Risk Index is formed by Likelihood score (from A, Minimum, to E Maximum) and Severity score (from 1, Negligible, to 5 Catastrophic) according to ECSS-M-ST-80C

		degradation of performance
B5	Failure of a single GRS system degrades science performance	- System is single-point failure tolerant by design - Direct flight heritage: LPF will fly the NGO GRS - The two arms interferometer of NGO is intrinsically susceptible to GRS failures
B5	Loss of one S/C will cause the end of mission	- Structural failures are not considered credible - All subsystems are required to be single-fault tolerant and most are fully redundant - Fault Detection, Isolation, and Recovery is being incorporated early in the design cycle - The two arms interferometer of NGO is intrinsically susceptible to GRS failures
C4	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 2 years prior to PDR
B5	Acquisition of the optical links through the telescopes between spacecraft not achieved	- 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
B3	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 and thrust authority for worst case tip-off rates - Battery sizing to worst case tip-off rates and ACS recovery time
C3	Microthrusters fail to meet LISA lifetime requirements	- Aggressive development of three independent thruster technologies (FEEPs, Cold Gas, MiniRits) - Identify and model life-limiting mechanisms, validate models - Accelerated testing to validate models and develop mitigations - Resiliency and redundancy built into the LISA

		design to minimize the lifetime requirements
B3	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
A4	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

9 ACHIEVEMENT OF REVIEW OBJECTIVES

The major objective set in the procedure for this review was:

Overall feasibility and credibility of the reformulated LISA concept for a launch in 2022 and an ESA CaC of 850 M€ (e.c. 2010)

The review of the preliminary design of mission elements has not evidenced any show stopper and the mission is considered credible and achievable. Some elements have been highlighted that will require attention in the next study phase.

The high degree of heritage from LPF has made the current mission design more robust compared to the previous LISA mission design. Together with the reuse of the same elements at spacecraft, propulsion module and payload assemblies level, this allows to rank the overall mission risk to medium.

The launch scenario with two Soyuz-Fregat is credible and the alternative possibility of a single Ariane V launch option offers additional flexibility in case of unexpected large mass growing.

On the assumption that the highlighted issues are resolved, the preliminary schedule and the overall duration for the mission development are considered credible.