Alternative Opto-Mechanical Architectures for the LISA Instrument

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Abstract. As part of the on-going LISA Mission Formulation study under ESA contract, EADS Astrium has recently suggested and investigated a variety of novel LISA payload architectures utilizing so-called “In-Field Pointing” for accommodation of seasonal constellation dynamics. Here, the annual variation in the angle between the interferometer arms of roughly ±1° is compensated by steering the lines of sight of the individual telescopes with a small actuated mirror located in an intermediate pupil plane inside the telescopes. This introduces a certain flexibility for the overall payload configuration and allows for very compact designs. In particular, it enables a “single active proof mass” mode with a true cold redundancy between a nominal and a backup GRS system on board each spacecraft, and thus enhances mission robustness.

1. Introduction
A main task of the recent phase of the LISA Mission Formulation study conducted by EADS Astrium under ESA contract has been the investigation of principal alternatives for the realization of the LISA opto-mechanical payload architecture. Although a well-consolidated baseline design utilizing two active proof masses had been developed [1–3], the investigation of other approaches to realize the LISA instrument is considered essential in order ensure that the optimum configuration for the mission is found, with respect to performance, technical feasibility, complexity, risk, maturity, implementation programatics, cost, etc.

One of the most promising alternatives to the original baseline configuration identified by EADS Astrium is a payload concept with only a single active proof mass per spacecraft, combined with the application of “In-Field Pointing” for the accommodation of constellation breathing. The underlying idea of this concept is that, from a conceptual point of view, a striking, intuitive, and elegant configuration for the LISA constellation would be one with a total of just three proof masses, located in full free fall at the corners of the constellation triangle, as schematically illustrated in Figure 1.

In-Field Pointing refers to one possibility for steering the active lines of sight of the two telescopes on board each spacecraft, which is necessary in order to follow the seasonal variation of the angle between the interferometer arms of the constellation triangle due to orbital mechanics. Beam steering is accomplished here within the field of view of each telescope by a small, actuated mirror, located in an intermediate pupil plane of the telescope. Since thus the telescopes can be rigidly attached to a common optical bench, In-Field Pointing integrates more coherently
Additional PMs may be added for redundancy.

Figure 1. Historic “Two Active PM” configuration (left) and pure drag-free “Single Active PM” configuration (right).

with a Single Active Proof Mass architecture than the alternative of “Telescope Pointing”. In Telescope Pointing, line of sight steering is accomplished by rotating the entire assembly of telescope, optical bench, and Gravitational Reference Sensor (GRS) as a whole, so that in principle each interferometer arm has to be delimited by its own proof mass.

While the technical realization of In-Field Pointing in compliance with the various performance requirements of the LISA instrument is extremely demanding, it still appears to offer a number of crucial benefits with respect to the original baseline configuration, when combined with a Single Active Proof Mass configuration:

- Since each spacecraft actively operates only a single GRS system at time, a full cold redundancy to a potential second GRS system on board can be realized. This improves mission reliability and mitigates issues concerning GRS caging.

- Depending on the choice of proof mass geometry, a virtually pure drag-free condition can be realized, thereby reducing the criticality of electrostatic guidance and noise. Even if the heritage from the LISA Pathfinder mission is maximized by maintaining a cubical proof mass shape, only the rotational degrees of freedom require suspension and a simplification of the DFACS design should remain possible. In particular, detrimental stiffness cross coupling from suspension of the lateral degrees of freedom is avoided, so that an overall reduction of acceleration noise on the PM appears feasible.

- By enabling a “single-piece” opto-mechanical system with a single optical bench, In-Field Pointing avoids the need for the so-called backside fiber link, which is required in architectures using Telescope Pointing to establish an optical phase reference between the two separate optical benches on board each spacecraft. Its feasibility in terms of reciprocal pathlength-stability has not yet been experimentally demonstrated to date, and thus remains a potential show stopper for the current baseline design.

- Telescope Pointing requires the actuation of a large mass with extremely low torque noise, which may not be representatively testable under 1g. In contrast, In-Field Pointing should ensure full on-ground testability of the beam pointing. Furthermore, a flexible harness to the payload core is avoided, so that potential impacts on the pointing performance due to harness cracking are mitigated. Launch locks for the pointing device are no longer required. Finally, continuous changes in self gravity due to breathing accommodation are minimized by the small size of the active components.

- In-Field Pointing introduces a high flexibility for the choice of the overall payload layout, and enables very compact and thermo-mechanically stable architectures. It thus provides the potential for savings in overall mass, volume, and power consumption with respect to the baseline configuration.
To demonstrate that the above features can principally be materialized, a coherent payload architecture with a Single Active Proof Mass and In-Field Pointing has been developed, solving in particular the two main challenges of designing a suitable telescope providing the required wide field of view in the plane of pointing, and controlling the pathlength variations caused by active pointing to an acceptable level within the measurement band.

2. In-Field Pointing

Since the seasonal variation in the angle between the interferometer arms is about $60 \pm 0.8^\circ$ [4], both telescopes on board each spacecraft require a field of view of at least $\pm0.5^\circ$ ($\pm9\text{ mrad}$) within the constellation plane, if the actuation range is shared between them and margin is included. Orthogonal to the pointing plane, i.e. in the out-of-plane direction, the required field of view is given by the maximum acquisition range to be accommodated, which is on the order of $\pm200\text{ mrad}$.

Further constraints driving the design of the telescope have been the need to minimize stray light into the receive path, as well as maintaining ease of accommodation without compromising optical pathlength stability. Both aspects are provided by the specialized off-axis system illustrated in Figure 2. It achieves an intrinsic avoidance of stray light through the absence of any obscuration in a fully reflective, two-stage design. The back optics is folded for straightforward interfacing with a vertical optical bench housing the main interferometry.

The design provides an intermediate pupil at a magnification of 10 for positioning of the “In-Field Pointing Mechanism” (IFPM) with a flat pointing mirror. An overall magnification of 100 compresses the 400 mm diameter virtual external pupil to an accessible internal pupil of 4 mm diameter. As shown in Figure 2, an excellent optical performance over the entire field of view is achieved. The design wavefront error is $<\lambda/100\text{ rms}$ for any pointing angle, with only minimal variations over the field.

A conceptual design for the IFPM, developed in collaboration with TNO, is depicted in Figure 3. It employs elastic Haberland hinges embedded in a monolithic of a stable material (TiAlV) to cover the required tilt range of $\pm2.5^\circ$. The actuation is based on a walking piezo motor, which combines high resolution with a large travel range, compatible to the required dynamic range of about $10^7$. This dynamic range is based on the allocation of a maximum of $1\text{ nrad}/\sqrt{\text{Hz}}$ contribution to the external line of sight jitter of each telescope, corresponding to

![Figure 2. Optical design (left) and optical performance (right) of the specialized wide-field, off-axis telescope. It provides an intermediate pupil for positioning of the In-Field Pointing Mirror (red box).](image)
Active pointing with the IFPM inside the telescope potentially introduces a new source of pathlength noise, as the system probes any dependence of the optical pathlength through the telescope on the pointing angle. While the nominal pointing adjustment on annual timescales in general will not produce spectral noise components within the measurement band of $10^{-4} – 1 \text{Hz}$, any coupling of pointing jitter to piston noise via this effect might be detrimental. Therefore, pathlength noise contributions driven by pointing jitter of the IFPM have been investigated in great detail, and in particular the following specific measures are taken to control these:

- The optical design of the telescope was tuned to minimize the sensitivity of the optical pathlength through the telescope to the pointing angle.
- Geometrical coupling of mirror tilt to piston is principally avoided by placing the IFPM in an intermediate telescope pupil and applying a Gimbal type mirror hinging.
- As illustrated in the middle panel of Figure 3, the mechanics of the Haberland hinge has been derived by FEM to determine the resulting piston motion of the IFPM mirror. By fine-tuning its position inside the holder, using only moderate adjustment tolerances of 10’s of microns, the effective piston due to hinge mechanics can be compensated to negligible amounts (Figure 3, right panel).

While these measures allow to reduce pointing jitter to piston crosstalk due to the IFPM to levels that can well be accommodated in the overall pathlength noise budget, EADS Astrium has nonetheless suggested an ancillary metrology system to monitor pathlength noise generated within the telescope. The underlying idea of this system, known as Active Optical Truss, is to refer the phase of the TX wavefront leaving the telescope directly to the optical bench reference frame. Hence, the application of this system is in general not restricted to this specific noise source, and thus can in principle be of benefit to any LISA payload architecture. In consequence, it has meanwhile been incorporated also in the present baseline architecture [4].

### 3. Adding Redundant GRS Systems

Since the LISA metrology is intrinsically referenced to the center of mass of each proof mass in the constellation, the location of these fiducial points is also restricted by geometrical projection effects resulting from pointing jitter. Ideally, as sketched in Figure 4, the proof masses should be located on their respective line of sight. To be more exact, the optical point of reference each proof mass must be aligned to is the phase center of its associated telescope, i.e. the point about which the spacecraft can be rotated without producing a pathlength signal.
As soon as the center of mass is offset from the phase center (right panel of Figure 4), a lateral lever arm $x$ is introduced, which again converts pointing jitter to piston noise. Since the effect is in principle deterministic, it can be calibrated, so that the applicable noise level is effectively that of the \textit{pointing knowledge}. The pointing knowledge, i.e. the measured value for the relative pointing between RX and TX beam in each telescope, is established by Differential Wavefront Sensing on the science receiver \cite{4}, and estimated to be on the order of 0.5 nrad/√Hz. In consequence, the lateral lever arm $x$ should not become larger than 2 mm to keep the associated noise contribution below about 1 pm/√Hz.

Given this small scale, adding a redundant GRS to a single active proof mass configuration in a geometry as depicted in the right panel of Figure 4 would unavoidably lead to increased measurement noise when switching to the redundant system. While such a graceful degradation of the measurement performance would probably be acceptable in a failure case, it nonetheless motivates measures to improve the pointing knowledge and thus increase the distance $d$ beyond which the measurement noise is compromised.

Since the main limit to the above mentioned pointing knowledge is given by pointing jitter of the Point Ahead Angle Mechanism (PAAM), which is used to adjust the relative pointing between TX and RX beam, the immediate approach is to reduce or at least more accurately monitor its jitter. Such a PAAM metrology system can be realized using the same metrology principles as already applied for the inter- and intra-spacecraft interferometry (see \cite{4}), and thus does not have significant impacts on the payload design and budgets. Like the Active Optical Truss, the robustness added by the PAAM metrology is thus beneficial in general, so that the latest baseline architecture also has inherited it.

4. Payload Architecture Variants

Based on the above considerations, a detailed opto-mechanical design for a payload architecture with a single active proof mass per spacecraft and the application of In-Field Pointing for accommodation of constellation breathing has been developed. It includes a single piece, vertical optical bench made from Zerodur, and a redundant GRS system in close vicinity to the nominal one, in line with the geometry shown in Figure 4. All payload components are supported isostatically from a low thermal expansion CFRP structure, which also provides the interface to the spacecraft.

The architecture is illustrated in Figure 5 together with all other payload variants that have meanwhile been established by EADS Astrium within the LISA Mission Formulation study.
Figure 5. Overview of investigated payload architectures. For the combination of Telescope Pointing with a Single Active Proof Mass, only a basic concept has been conceived, confirming that it does not lead to a useful overall solution. The models are not to scale.

Notably, In-Field Pointing can also reasonably be combined with two active proof masses per spacecraft to yield an extremely compact payload, smaller in size than any other design so far. The baseline configuration currently selected by ESA however falls back to the more historic Telescope Pointing [4].

In conclusion, EADS Astrium has meanwhile explored the trade space of alternative payload architectures for the LISA instrument in great detail, and demonstrated that payload architectures utilizing only a single active proof mass per spacecraft are feasible, attractive, and do not show principal show stoppers.

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