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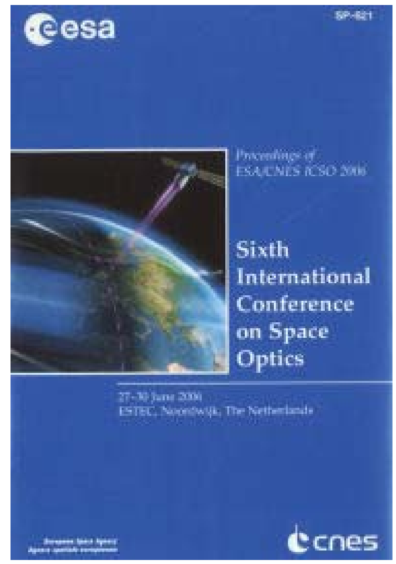

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NOVEL PAYLOAD ARCHITECTURES FOR LISA

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ABSTRACT

The present LISA (Laser Interferometer Space Antenna) gravitational wave detector concept features three satellites in individual earth trailing helio-centric orbits, which are linked by bi-directional monostatic laser interferometry between free-falling inertial reference masses inside the payload. The spacecrafts are maintaining an equilateral triangular constellation with 5 Million km armlength. The optical payload consists in the present configuration out of two assemblies, each one comprising a telescope, an optical bench and an inertial sensor and serving one arm of the adjacent interferometers. Due to orbital distortions, the constellation triangle is not perfectly maintained, but the line of sights offset angle is slowly changing during a one year revolution by 60°±0.75°. This variation is far beyond the diffraction limited beam width (2.5 µrad) and hence requires active compensation presently done by actuation of the complete assemblies. While allowing almost stationary on-axis operation of the optics, the arrangement requires two separate active inertial sensors, a rather sophisticated optical interfacing between the interferometer arms and active electrostatic suspension of the test masses in all but one degree of freedom.

We identified an alternative architecture, characterized by a single operational inertial sensor and a single optical bench serving both adjacent interferometer arms. Both telescopes are rigidly fixed to the optical bench and the angular breathing is accommodated by in-field of view pointing of transmit and receive beams via on-bench actuation mechanisms. Only attitude electrostatic actuation of the test mass is required, which can be kept otherwise in free fall. Such an architecture requires a decoupled inter- and intra-spacecraft metrology in two steps linked via optical bench fiducial points (strap-down). Peculiar technical challenges are the actuation mechanism and the inherent metrology to calibrate or compensate within the LISA measurement band –at pm and nrad resolution- for laser phase and pointing changes, respectively, inside the optical assembly.

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1. INTRODUCTION

The LISA mission aims at detection of gravitational waves excited in space-time by accelerated compact objects either in periodically (e.g. neutron star or black hole binaries) or as transients (e.g. neutron star/black hole mergers). It opens a new radiation window to the universe at a low frequency band not accessible from ground [1].

The mission is planned as a joined ESA NASA activity with Astrium Germany currently being in charge of an ESA mission formulation study.

The LISA mission duration is 6.5 years with a possible extension to 10 years. The three LISA spacecrafts are injected into their individual heliocentric orbits via dedicated, jettisonable, chemical propulsion modules after a Delta 4 launch. An equilateral triangular constellation of three spacecraft, separated by 5 million km from each other and mutually linked by heterodyne laser interferometry in an active transponder scheme, is trailing the earth in their heliocentric orbits at an angular offset of about 20°. The triangular plane is revolving over the year, while keeping its normal at 30° tilted with respect to the plane of the ecliptic and pointed towards the sun. The laser interferometers along each arm are referenced to dedicated free falling test masses (cubes) inside the payload. They are kept in their free-fall condition (along the associated laser interferometer axis only and within the desired measurement bandwidth 10^{-5} Hz to 10^{-1} Hz) by a "drag-free" control system, minimising acceleration distortions from space environment and the surrounding spacecraft itself. The local optics attitude is locked relative to the incoming wavefront planes of the received beams via differential wavefront sensing in the main heterodyne detection chains. The link budget features about 1 W and 100 pW of the 1064 nm laser in the transmitted and received beam, respectively for 400 mm telescope aperture. Gravity waves passing the constellation cause pm differential piston/phase modulation of the laser interferometers, detectable by signal processing of all laser heterodyne phase meters which generate beat notes between local and received lasers for all interferometers. The detection sensitivity is constrained in the low frequency band by test mass acceleration noise (e.g. thermo-elastics, electrostatics), in the medium range by laser photon statistics (laser power) and in the high end by antenna (arm length) mismatch.

2. TECHNICAL CHALLENGES OF THE LISA MISSION

The engineering challenge, in the first place, is the minimisation of technically induced accelerations on the test masses and of laser interferometry phase noise within the measurement band. This translates into demanding, but feasible technical requirements on laser assembly phase noise suppression by on-board measures (active stabilisation and arm locking) and on-ground signal processing (time delayed interferometry) and the control of all technically induced phase effects on the laser modulation and heterodyne phase detection chain. Further, tight requirements are imposed for thermal and thermo-elastic stability in the opto-mechanical chain, comprising telescope and optical bench, as well as on precise test mass relative attitude and position sensing, thruster noise, EMC and self gravity compensation.

For the optics interferometry itself, the main technical challenges to meet the measurement performance can be grouped into four areas:

- Minimize technically induced laser piston/phase fluctuations within the measurement band in both, the transmitted and received beam between local phase references on the optical bench to the system aperture (entrance pupil).
- Provide active transmitted and received beam guidance and pointing stability within the measurement band.
- Minimize cross talk effects from pointing jitter to laser beam phase jitter within the measurement band and caused by geometric projection effects.
- Minimize straylight and polarisation impact on phase detection performance.

While opto-mechanical stability requirements are typical for demanding coherent interferometry systems (e.g. ground based laser interferometers), albeit special in LISA due to the very low frequency measurement band, the dynamics of the LISA constellation imposes some peculiar challenges, which are largely driving the payload architecture.

The deviation from an ideally, intrinsically stable LISA triangular constellation with equal arms, resting in an inertial frame, leads to following effects:

- Unequal interferometer arm length: laser phase noise dominates phase detection if not compensated for.
- Angular variation within the triangular plane: line of sight lateral offset angle “breathing” around 60°.
- Radial distance variation within the triangular plane: Doppler shift of laser frequency to be accommodated by heterodyne detection.
- In-plane rotation of constellation: fixed offset pointing (nearly) between transmit and received beam.
- Revolution of constellation plane orientation: variable offset pointing between transmit and received beam perpendicular to plane.

The LISA dynamics causes slow relative pointing changes of the adjacent interferometer arms line of sight directions by 60°+-0.75° for the presently selected orbit parameters as well as Doppler shifts of about +-20 MHz along the line of sights, both features following a sinusoidal annual pattern. Both figures could be reduced to 60°+-0.35° and 14 MHz, respectively, by increasing the distance from earth on cost of a more difficult mission operation. As uncovered in the previous study [2], the finite roundtrip time combined with the angular velocity of the line of sight causes an annual sinusoidal varying offset (point ahead) angle of +- 6 µrad between transmit and received beam and perpendicular to the constellation plane. That value already vastly exceeds the diffraction limited beam divergence of about 2.5 µrad. The addressed group of effects is requiring dedicated mechanisms to precisely sense and actuate common and differential line of sight directions, respectively, as well as a laser frequency map and beat note down-mixing scheme.

The present Astrium study has uncovered also further geometrical projection effects in the near and far field of the laser beams (at local or remote spacecraft, respectively), causing pointing jitter to piston/phase jitter cross talk within the measurement band not tolerable for the measurement requirements. These geometrical effects appear at various places in the measurement chain:

- Test mass attitude to piston jitter crosstalk caused by lateral offset of inertial sensor optical readout beam effective line of sight with respect to the test mass centre.
- Transmitter beam line of sight jitter (caused by local spacecraft attitude jitter) crosstalk caused by lateral offset of the outer space line of sight -projected backwards- with respect to the test mass centre.

- Received beam phase jitter, caused by remote spacecraft pointing jitter and a mismatch of jitter centre and phase centre.
- Received beam line of sight jitter (due to local spacecraft attitude jitter) crosstalk caused by lateral offset of the outer space line of sight - projected backwards- with respect to the test mass centre.
- Optical path length changes encountered by the beam while re-pointing or jittering and caused by optical imperfections (substrate inhomogenity, optical surface aberrations "phase walk", actuated mirror pointing jitter and piston bias, tolerances in pupil planes locations)

Locally, the backwards projected line of sight direction in outer space intersecting the phase centre (not the physical laser beam routing itself), has to pass within tight tolerances through the associated test mass centre of mass, representing the measurement reference. That holds for both, the transmitted and received beam, following different routs on the optical bench. The actual beam routing on the optical bench is irrelevant for these effects. The laser beams phase centres have to coincide with the measurement reference point accurately enough to keep the pointing jitter to piston/phase jitter crosstalk within acceptable limits. The tight tolerances resulting for the beam alignment and there verification are extremely challenging. For the transmitter beam, a truncated Gaussian, the radiometric centre (line of sight) has to be aligned laterally within millimetre with respect to the telescope pupil geometry. For the received beam, the entrance pupil cuts out a top hat beam routed to the heterodyne sensor, where the radiometric centre must coincide within few µm with the preset position. It is important to note that the beat notes from the quadrants of the heterodyne sensor can be weighted and must be calibrated to laterally shift the "virtual" radiometric centre of the received beam (the virtual line of sight lateral offset) to a known and minimal value.

The far field effect corresponds to optical aberrations offsetting the laser wavefront phase centre and the pointing jitter centre, mainly due to defocus and astigmatism [1, 2]. The optical design has to cope with this requirement within the aberration budget.

Still, cross talk from pointing jitter to laser phase jitter cannot be avoided within achievable alignment and radiometric calibration tolerances, combined with feasible attitude control authority (typ. 10 nrad/√Hz in outer space). Hence, Astrium proposes to utilise the very accurate and sufficient instantaneous pointing knowledge provided by the differential wavefront sensing of the heterodyne phase meters (200 prad expected) to correct the phase signal accordingly after in orbit calibration of the crosstalk function. That approach has significant impact on system and optics design. The corresponding data have to be transmitted to ground for signal post processing. Further, as the pointing reference is the incoming wavefront plane at the location of the entrance pupil but sensed by the heterodyne science detector, any "weak" pointing transfer en route degrades the pointing (jitter) knowledge. Challenging pointing jitter requirements result for actuators in the path (point ahead, breathing angle compensator).

Similar crosstalk effects are encountered in the laser beam to test mass interaction (acting as active mirror), but can be mitigated again by precise knowledge of test mass attitude and position relative to the laser beam fiducial points. This information is also provided by a dedicated differential wavefront sensing optical readout for the inertial sensor. Interestingly, the problem is already present in LISA Pathfinder.

The cross talk effects are always present, independently of a particular payload configuration and optics realisation. They are simply a result of the system geometry and dynamics. However, their mitigation has a strong impact on the optical system configuration and technical realisation, and is specific for the various architectures under consideration.

3. LISA PAYLOAD CONFIGURATION BASELINE

Astrium has evolved the payload architecture considerably during the first part of the present study in order to cope with these challenges and further, to arrive at a robust architecture of the payload with optimised mass and power budgets and assembly and verification procedures. In particular, two step interferometry (strap-down) already conceptually proposed by Astrium in [2] has been adopted now as baseline. Details on the present architecture can be found in these Proceedings in [3].

The present payload configuration –albeit still requiring dedicated development effort- is considered to be consolidated and feasible. It also incorporates the LISA Pathfinder Instrument (LTP) technology in an effective way. It is designed to keep the optical path inside the assemblies stationary and to largely separate functionally the two adjacent interferometer arms. Nevertheless, in the desire to further simplify the system and to potentially reduce costs, complexity and physical budgets, alternative solutions with that potential have been identified and preliminary assessed. It should be pointed out however, that it is too early to trade the architectural alternatives at this stage due to the not comparable maturity of analysis. The following sections hence reflect the current status of investigations only.

4. ALTERNATIVE PAYLAD CONFIGURATION

A promising novel concept is characterized from optics point of view by a single optical bench and active inertial sensor, serving both adjacent interferometer arms via two rigidly connected off-axis telescopes. The "breathing angle" compensation is accomplished by in-field of view pointing actuation of the lasers line of sight. Single inertial sensor concepts are an obvious choice in an attempt to simplify the LISA payload. A big advantage would be that no sophisticated electrostatic suspension and capacitive readout is required. For a cubic test mass, only a presumably simple attitude suspension is necessary; for a spherical test mass no suspension at all is necessary. The spacecraft simply follows the test mass in free fall guided by a sensitive optical readout of the relative position to the optical bench and in attitude by the incoming wavefronts from the adjacent spacecrafts. However, intriguing at first sight, these concepts have their specific problem areas. Only concepts featuring a combination of suitable line of sight articulation and single optical bench/active inertial sensors are of particular interest. Also the redundancy implementation at various system levels is not as obvious as in the present baseline.
Fig. 1 illustrates a first not yet optimized architecture of such a payload assembly.

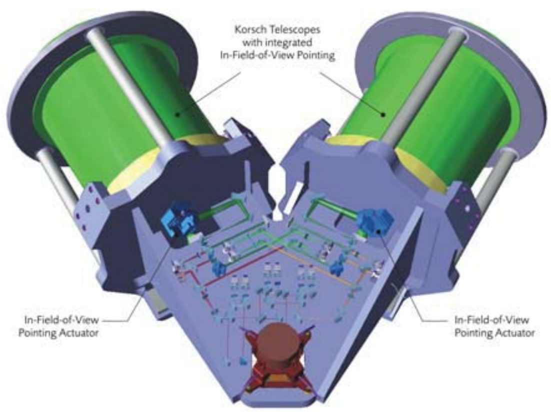

Figure 1. Single test mass payload configuration for LISA. The inertial sensor is located on a single optical bench and similar to the LISA Pathfinder design, albeit with optical readout on lateral degrees of freedom in the plane. The two lasers are phase correlated directly on the bench. The two symmetric Korsch type telescopes are rigidly connected and the in-field pointing is provided by two on-bench actuators acting on transmit and received beam. Also the perpendicular to the plane operating point ahead actuators (in the receive beam path only) are integrated (small blue boxes).

The fixed geometry in a rigidly connected architecture -comprising the two telescopes, the optical bench and the inertial sensor- dictates the locations of the telescope pupils and the test mass centre. As a caveat of this rigid assembly, the projected line of sight will not always intersect the test mass centre, but -following the breathing angular variation by in field of view pointing- will suffer lateral offsets of a few mm, increasing the pointing jitter crosstalk (see section 2) sensitivity periodically. In order to minimize the dependency, the telescope pupil plane should be as close as possible to the test mass centre e.g. in the M1 plane. A dedicated actuation mechanism located on the optical bench now is necessary in addition to the always required point-ahead actuators. A technical challenge here is the actuation mechanism pointing jitter to be kept at <1nrad/$\sqrt{}$Hz (for an optical demagnification of 10) and the monitoring and calibration of the laser phase walk occurring, while changing the optical path inside the optical assembly during re-pointing. Presumably, an internal laser metrology truss derived from the existing interferometry is required to accomplish this task. The scheme is exploiting the 2-step interferometry in full and employs a dedicated full laser interferometer (ORO) read out of critical degrees of freedom of the test mass. The single test mass is still cubic, but in free-fall in the lateral degrees of freedom within the constellation plane. Also the option of a completely free falling spherical test mass with full laser interferometer readout has been conceptually investigated. The spherical test mass would rotate slowly (1 Hz), would not be spin controlled, but be allowed to tumble. Imperfections in roundness and density, which would be coped with, by providing attitude information via a grid of tick marks etched onto the surface and monitored by the laser readout. Any imperfections could be calibrated during commissioning by mapping in a high spin mode.

4.1 Payload System Architecture

A conceptual payload architecture is shown in Figure 2. Here, the telescopes are off-axis to reduce straylight stemming from an M2 spider in symmetric designs. The in-field pointing actuators are combined in a single mechanism located on the symmetry axis of the assembly. The pointing jitter induced by actuator noise is monitored by a dedicated heterodyne interferometer derived again from the existing infrastructure on the bench.

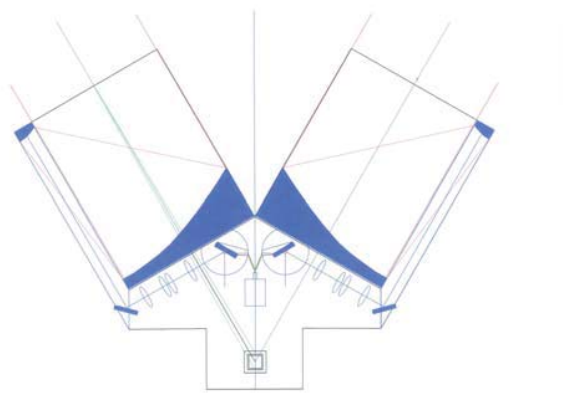

Figure 2. Conceptual architecture of a single test mass based LISA payload concept. The concept is featuring off-axis Korsch type telescopes and in-field guiding in the plane of the constellation by actuated mirrors in a pupil plane image. The drawing is to scale, but the relay optics is illustrated only. The pointing mirrors, actuated by +-7.5° (at V=10) are driven by a single mechanism. The mechanism jitter in the measurement band is monitored/controlled by a dedicated heterodyne laser interferometer derived from the already existing on-bench laser beams, similar as in the case of the optical inertial sensor readout..

4.2 Fixed Off-Axis Telescopes

The main reason to consider off-axis telescopes is the minimisation of straylight and back reflections from M2 elements. Also the accommodation of the actuator mirror is easier as compared to symmetric designs. A further consideration in telescope design is an all-reflective layout in order to minimize thermally induced path length fluctuations by long stretches inside a transmissive elements chain (lenses). Figures 3 and 4 show a first optical layout for a Korsch type off-axis telescope with 400 mm aperture, capable of in-field guiding +-1.5° (margins included).

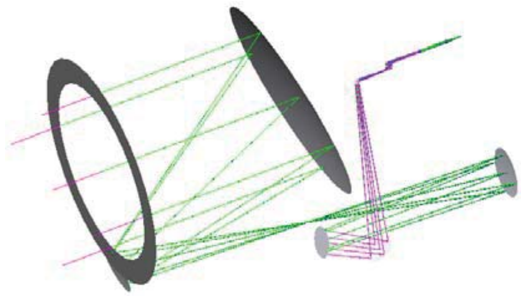

Figure 3. Asymmetric Korsch all reflective three mirror design at WFE <λ/20 and suitable pupil plane locations capable for in-field guiding by +-1°

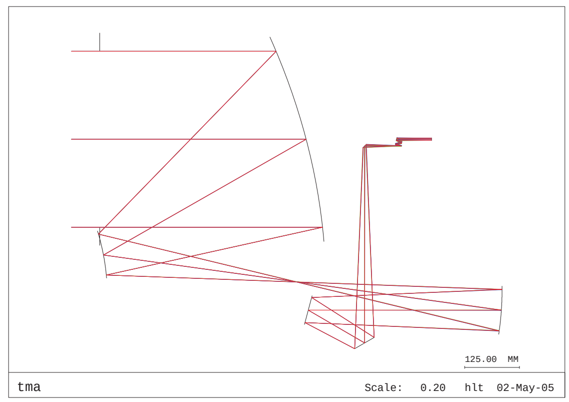

Figure 4. Optical layout of the asymmetric Korsch in Figure 3. The in-field beam steering is walking the beam perpendicular to the plane.

5. CONCLUSIONS

The LISA payload architecture has been consolidated in an on-going Astrium study carried out for the European Space Agency. The study has investigated known and newly uncovered geometric projecting effects in the optical system, causing pointing jitter to laser phase jitter crosstalk. Technical countermeasures influencing payload architecture have been identified and analysed. An alternative payload architecture based on a single inertial sensor serving both arms and on fixed telescopes with in-field guidance of transmit and receive beams has been identified and conceptually defined. Work at Astrium is on-going to refine the new architecture and to allow a sensible cross comparison of the concept alternatives.

7. ACKNOWLEDGEMENTS

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