Control System Design for the Constellation Acquisition Phase of the LISA Mission

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Abstract. The objective of the constellation acquisition phase for the LISA mission is to establish the three laser links between the three spacecraft of the LISA constellation so that the interferometric measurements for the science experiment can commence. The laser beam acquisition for LISA is extremely challenging given the 5 million km distance between the spacecraft, the inherent limits of the attitude sensors accuracy, the orbit determination accuracy issues and the time required to phase-lock the incoming and outgoing laser signals. This paper presents the design of the control system for the acquisition phase of the LISA constellation: the acquisition operational procedure is outlined, guidance laws are defined together with the Gyro Mode attitude control principle, which implements a Kalman filter for disturbances rejection purposes. Constellation-wide non-linear simulations demonstrate that the LISA constellation acquisition phase is feasible by means of the proposed control strategy.

1. Introduction
The main goal of the LISA mission is to detect gravitational waves and characterize their sources. The underlying measurement principle is a laser interferometry system built up with three identical satellites, each carrying two telescopes for laser pointing and flying in a triangular constellation with an edge length of $5 \cdot 10^6$ km. Nevertheless, the interferometric measurements for the LISA science experiment are only possible once the three laser links between the three LISA spacecraft are acquired on the six quadrant photodiodes (QPD) (one for each optical bench, i.e. one for each telescope) so that the QPD can start to measure the arm-length variations with a few picometer accuracy and to operate as a highly accurate inertial wavefront sensing for the spacecraft and telescope attitude control.

The constellation acquisition phase for the LISA mission is strongly demanding given the distance between satellites and the laser beam pointing determination issue which is mainly related to the inherent limits of the attitude sensor accuracy and to the orbit determination uncertainties.

In fact, the acquisition uncertainty half-cone angle, i.e. the size of sky where the receiving spacecraft is expected to be located w.r.t. the sending spacecraft, is estimated to be $15.2 \, \mu$rad and it has contributions from the navigation error, the laser beam pointing long-term drift due to the accuracy of the available attitude sensors and the alignment accuracy between star-tracker (STR), telescope line-of-sight (LOS) and outgoing laser direction. The laser beam half-cone angle at the receiving side, instead, spans $1.43 \, \mu$rad being the full-width of the emitted beam at half-maximum reduced by the local laser beam pointing short-term drift due to the attitude sensor accuracy. Since the uncertainty cone is larger than the laser beam cone, the acquisition cannot be direct. Moreover, since the QPD
field-of-view (FOV) is 1 µrad, and therefore smaller than the laser beam cone size, a fine acquisition strategy must be foreseen.

The attitude sensor accuracy issue arises from the fact that the QPD is not available until it receives a continuous laser signal. Therefore, a star tracker, together with an optical assembly tracking mechanism (OATM) sensor, must be used as auxiliary coarse attitude sensor when no links are acquired. A fine accuracy acquisition sensor (CCD) can then be used for laser pointing determination when the CCD itself has acquired a laser signal and under the condition that the local laser is off. The current baseline for sensor equipment is shown in table 1: in order to enhance the FOV and the resolution required to realize the measurement chain from one sensor to another, also a drastic increase in the read-out noise is produced.

|                  | STR       | CCD        | QPD       |
|------------------|-----------|------------|-----------|
| **Field-of-View**| 0.3 rad   | 155 µrad   | 1 µrad    |
| **Resolution**   | 255 µrad/pixel | 0.4 µrad/pixel | 1 nrad/pixel |
| **Read-Out Noise**| 29 µrad (RMS 3σ) | 60 nrad (RMS 3σ) | 750 prad/√Hz |

The design of a dedicated acquisition control strategy was therefore mandatory in order to perform the constellation acquisition phase for the LISA mission. Such a strategy includes:

- The establishing of an acquisition operational procedure.
- The design of the control system: guidance laws, measurement processor and controller.
- The set up of a constellation-wide non-linear simulator to verify that the LISA constellation acquisition phase is feasible by means of the proposed control strategy.

### 2. Constellation Acquisition Operational Procedure

In order to fulfill the LISA constellation acquisition a dedicated Laser Beam Acquisition Mode must be used. Spacecraft are first placed in Gyro Mode so that the inertial sensor measurements of the test masses states are used as gyro-like measurements to filter, smoothen and propagate the STR data and the OATM sensor data for disturbances rejection purposes. After a transient period, spacecraft point at each other based on ground-provided ephemeris data, STR and OATM sensor measurements (Steady State Mode). The strategy adopted for the constellation acquisition is then sequential in the sense that it establishes one laser link at a time. The process for the single-link acquisition is initiated from ground command and then accomplished autonomously as described in the following section.

#### 2.1. Single-Link Acquisition Process

The single-link acquisition process is divided into three main phases: a signal acquisition on the CCD, a signal fine acquisition on the CCD and a signal acquisition on the QPD.

2.1.1. **Signal Acquisition on the CCD.** The goal of this acquisition step is to find the laser signal on the CCD of both spacecraft (S/C). The sending S/C turns on the laser and performs a scanning maneuver to cover the whole uncertainty cone while the receiving S/C holds its reference attitude based on ground-provided navigation data. At a certain time during the scanning, the receiving S/C detects a laser signal on its CCD, estimates the offset between the real and the ground-provided incoming laser signal, performs an attitude offset correction and switches on its laser. However, only after switching off its local laser at the end of the scanning maneuver, the sending S/C can detect a signal on its CCD and, analogously to the receiving S/C, apply the necessary attitude correction to its on-board reference attitude by steering its telescope to the updated reference direction. Both spacecraft along one arm of
the constellation have now acquired a laser signal on their CCD but the laser transmission cannot be continuously operated yet, since the CCD is blind when the local laser is activated.

2.1.2. Signal Fine Acquisition on the CCD. Sending and receiving S/C perform a fine attitude correction by switching lasers on/off in order to bring the incoming laser signal to a reference position of the CCD within the FOV of the QPD. CCD measurements are used to support attitude control (CCD Mode). This sub-phase may be bypassed if Gyro Mode performances allow getting a signal on the CCD which is already within the QPD field-of-view.

2.1.3. Signal Acquisition on the QPD. In order to obtain the laser signal on the QPD of both S/C along one constellation arm, the receiving S/C performs a frequency scan by changing the frequency of its local laser in order to detect an interference signal on its QPD. Once the receiving S/C has found a beat signal, the sending S/C will also find a beat signal approximately 16.7 s later, i.e. the delay of any information travelling through the 5·10⁶ km arms between the satellites. As for the fine acquisition, CCD data can be used to support attitude control depending on Gyro Mode performances.

2.2. Laser Link Acquisition Sequence
The single-link acquisition process must be repeated three times in order to establish the three laser links between the LISA spacecraft. The order in the link acquisition is arbitrary: the sequence illustrated in figure 1 has been selected just as exemplification. Note that the arrows indicate the direction of traveling light. Note also the configuration of the telescopes (figure 2): telescope 1 (T1) is actuated and can be rotated in the constellation plane, while telescope 2 (T2) is fixed to the S/C. The first laser link to be established is link L₃/L₃’ where T1 of S/C1 defines the sending pointing direction and T2 of S/C2 defines the receiving pointing direction. Then, the acquisition of the link L₂/L₂’ is performed with T2 of S/C1 as sender and T1 of S/C3 as receiver. Eventually, the laser link L₁/L₁’ is acquired where T1 of S/C2 is the sending direction and T2 of S/C3 is the receiving direction.

3. Constellation Acquisition Control System
The key element to perform the constellation acquisition for the LISA mission stands in the design of the acquisition control system. This is divided into three parts: a guidance law design capable to drive the laser pointing during the acquisition, a measurement processor design necessary to reduce the disturbances on the telescope pointing due to the coarse attitude sensor noise and a controller design.

Three cases can be considered for attitude determination during the acquisition phase:

- No available fine attitude sensor measurements: attitude determination must be achieved by means of a measurement processor used to reject the sensor noise conveyed by the STR.
- One link of fine sensor data (CCD, QPD) available: fine sensor data can be used with or within the measurement processor to provide higher-accuracy attitude knowledge. The CCD Mode can be necessary to perform fine pointing and to achieve QPD acquisition while QPD data can be used to improve the acquisition of the second S/C arm once the first is acquired.
Two links of fine sensor data (QPD) available: QPD data can be exclusively used to compute the telescope pointing as in Science Mode.

It has been conservatively assumed for the design of the control system that only the STR and the OATM sensor data are available during the whole duration of the constellation acquisition phase [1].

3.1. Guidance Law Design

Three different guidance laws are derived in order to drive the telescope pointing during the several constellation acquisition sub-phases.

The reference attitude law for the Gyro Mode is based on ground-provided ephemeris data, including point-ahead angle computation and compensation, where the point-ahead angle is the angle between the send and the receiving direction due to the relative motion of the S/C in the constellation.

The scanning law selected for the scanning maneuver consists in Archimedean spiral motion from the center, where is more likely to find the receiving S/C, to the outer boundary of the uncertainty cone, performed with constant tangential velocity. The parametric equations of the spiral motion are:

\[
\begin{align*}
\rho &= \frac{k \cdot r}{\pi} \cdot \theta \\
\theta &= \left( \frac{2 \cdot \pi \cdot a \cdot (t - t_0)}{k \cdot r} \right)^{1/2}
\end{align*}
\]

and additional conditions derived by imposing to cover the uncertainty cone in \(N+1\) rounds are:

\[
N = \left( \frac{R}{k \cdot r} \right) \cdot \frac{1}{2}
\]

\[
a \cdot \Delta t_{id} = 2\pi \cdot k \cdot r \cdot (N + 1)^2
\]

where \(R\) is radius of the uncertainty cone (~ 76 km), \(r\) is the radius of the laser beam cone (~ 7.15 km), \(k \in [0,1]\) is the spiral pitch, \(N+1\) are the rounds required to cover the uncertainty cone, \(a\) is the constant tangential velocity, \(t_0\) is the starting scanning time, \(t\) is the current time and \(\Delta t_{id}\) is the ideal time required to cover the uncertainty cone. Note that \(k\) and \(\Delta t_{id}\) are the only free parameters and must be tuned in order to guarantee a sufficient coverage of the uncertainty cone.

The guidance law selected for the attitude offset correction is a time-optimal slew maneuver with torque and angular velocity limits. Details on the governing equations can be found in [3], nevertheless it is important to point out that the maneuver is completely determined once the maximum torque delivered by the actuators and maximum angular velocity permitted by the sensor equipment or by the controller are selected.

3.2. Measurement Processor and Controller Design

Since the STR does not provide a good enough attitude reference, the inertial sensor (IS) is used to support the attitude control system over short time-periods. This control mode is addressed as Gyro Mode since it is based on the same principle, which is often used for spacecraft attitude determination in high accuracy pointing applications and which relies on the hybridization of STR and gyroscope measurement data. In analogy to the STR and gyros data fusion approach, the IS data are used as gyro-like measurements to filter, smoothen and propagate the STR data, supporting in this way the attitude control system over short-time periods. This can happen because the two signals have complementary error characteristics: the STR has a good long-term stability but suffers from short and medium-term noise, on the contrary the IS (“gyro”) has a good short-term stability but suffers from medium and long-term drifts due to unknown or uncertain DC forces and torques acting on the test masses.

The way to implement the Gyro Mode is to use a state-augmented continuous-time steady-state Kalman filter opportunely tuned, whose detailed equations can be found in [1] and [4], that processes
the measurement data coming from all the available sensors (STR, OATM sensor and IS unit) providing enhanced estimates of the S/C attitude, the T1 in-plane pointing angle and the test masses coordinates. The enhanced estimations are then fed in closed-loop to the controller in place of the sensor data. The controller used in acquisition mode has the very same structure of the drag-free and attitude control system (DFACS) used in Science Mode. Details about the DFACS can be found in [5].

4. Performances Analysis

The end-to-end (E2E) constellation non-linear simulator shown in figure 3 has been developed in order to analyze and validate the proposed control strategy in a time domain framework and, therefore, to demonstrate the feasibility of the LISA constellation acquisition.

**Figure 3.** Main structure of the LISA E2E constellation simulator. It consists of three individual spacecraft running in parallel and connected via six arm delay models. Spacecraft can be independently configured by means of separate telecommanding blocks. The model includes the full rigid-body dynamics of the LISA constellation: non-linear dynamics with 57 degree-of-freedom including spacecraft, telescope and test masses states, reference attitude computation via Chebychev propagator algorithm with point-ahead angle compensation, DFACS control system, detailed actuator and sensor models.

Figures 3 and figure 4 show the time series of the telescope pointing performances during the acquisition of the laser link L₃/L₃'.

**Figure 3.** Time series of the telescope 1 pointing of spacecraft 1 (L₃').
The use of the Kalman filter and the choice of an appropriate spiral pitch guarantee that the laser beam of spacecraft 1 is able to map the whole uncertainty cone with a coverage varying between 1.8 s and 8.6 s. The time required to complete the laser link acquisition is about 1400 s (ca. 24 minutes). The telescope pointing performances during the acquisition of the remaining two links are basically the same and are not shown for editorial reason (see [4] for details). The resulting total duration of the constellation acquisition phase is about 70 minutes, that is 100 minutes including margins.

**Figure 4.** Time series of the telescope 2 pointing of spacecraft 2 (link L₃).

Figure 5 shows the complete time series of the telescope pointing errors from the starting of the *Gyro Mode* up to the end of the constellation acquisition phase.

**Figure 5.** Time series of the six telescope pointing errors during LISA constellation acquisition.
The angular offsets between the telescope pointing direction and the direction of the incoming laser beam for each arm of each satellite are shown. After a transient period of about 12000 s, the Gyro Mode achieves the steady state and non-zero offsets, larger than the laser beam cone size, affect all the constellation arms: no signal can be detected. The acquisition phase begins at 17000 s and ends about 5500 s later. The residual misalignment between the pointing direction and the laser beam incoming direction is lower than the laser beam cone size, i.e. 1.43 µrad, and, moreover, lower than QPD field-of-view, i.e. 1 µrad, indicating that the Gyro Mode performance allow getting a signal on the CCD which is already within the FOV of the QPD.

5. Conclusions
A control strategy for the acquisition phase of the LISA constellation has been proposed: it includes the definition of an operational procedure, the design of a constellation acquisition control system and the development of an E2E constellation simulator.

Constellation-wide non-linear, fully coupled E2E simulations demonstrate the feasibility of the laser beam acquisition from initial scanning up to Science Mode for all constellation arms. The total duration of the acquisition phase results in about 70 min, i.e. 100 min including margins.

The acquisition phase is entirely performed in Gyro Mode. Time domain analyses indicate that Gyro Mode performances meet the requirement for a CCD acquisition directly in the QPD field-of-view in a timely manner. However, even if a fine acquisition is not strictly required, its implementation is advisable in order to guarantee larger safety margins for the QPD acquisition.

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