

Possible Periodic Orbit Control Maneuvers for an eLISA Mission

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Abstract.

This paper investigates the possible application of periodic orbit control maneuvers for so-called evolved-LISA (eLISA) missions, i.e., missions for which the constellation arm lengths and mean distance from the Earth are substantially reduced. We find that for missions with arm lengths of $\sim 10^6$ km and Earth-trailing distance ranging from ~ 12 deg to 20 deg over the science lifetime, the occasional use of the spacecraft micro-Newton thrusters for constellation configuration maintenance should be able to essentially eliminate constellation distortion caused by Earth-induced tidal forces at a cost to science time of only a few percent. With interior angle variation kept to $\sim \pm 0.1$ deg, the required changes in the angles between the laser beam pointing directions for the two arms from any spacecraft could be kept quite small. This would considerably simplify the apparatus necessary for changing the transmitted beam directions.

1. Introduction

A gravitational wave mission called the Laser Interferometer Space Antenna (LISA) was under study for some time as a proposed joint mission of ESA and NASA (ref Sallusti et al. (2009); ref ESA (2011)). It consisted of a nearly equilateral triangle formed by three spacecraft, with 5-million-km long baselines between them. Changes in the distances between reference test masses in the different spacecraft due to gravitational waves would be measured by laser interferometry along the baselines. The triangle was to be located about 20deg behind the Earth, in a one year period nearly circular orbit around the Sun.

In order to minimize variations in the lengths of the baselines, each spacecraft would be given an eccentricity e of about 0.01 and an inclination of $\sqrt{3}$ times this size (ref Sweetser (2005a); Povoleri & Kemble (2006)). With proper initial conditions for the orbits, the plane of the triangle would be tipped at 60deg to the ecliptic. From Kepler's laws, neglecting planetary perturbations, the amplitude of the time variations in the distances D_{ij} between the spacecraft pairs ($ij = "12", "23", "31"$) along the interferometer arms could be made as small as $e/2$ times the mean arm length D , or about 0.5% (ref Sweetser (2005b), eq. 30):

$$\delta D_{ij} = (15/32)eD \cos[L + \phi_{ij}] + (1/32)eD \cos[3(L + \phi_{ij})] \quad (1)$$

Here $L = nt$ is the mean longitude of the centre of the triangle, n is the mean motion, and ϕ_{ij} is a phase angle of 0 deg, 120 deg, or 240 deg. The corresponding variations in the angles of the triangle would be about 0.5deg.

The preceding description was without consideration of the Earth's gravitational perturbations. However, even 20deg away from the Earth, the gravitational perturbations would cause substantial secular variations in the triangle geometry. By choosing the orbit initial conditions carefully, the amplitude of the variations in the angles of the triangle for the original LISA mission could be kept down to about 0.8deg over a roughly 8-year total mission lifetime. In order to accommodate such changes in the angles between the directions in which the laser beams

from a given spacecraft had to be pointed, each transmitting telescope and its associated optical system was mounted in an “optical assembly” that could be rotated by small amounts with respect to the main spacecraft structure.

We will take the main characteristic of evolved LISA (eLISA) type missions (ref Danzmann (2012)) to be 1-million-km arm lengths. To understand the situation better, we first consider what would happen if there were no perturbations due to the Earth or planets. In this case, the natural Kepler variations in the angles of the triangle would be reduced by a factor of 5 with respect to those for LISA, to an amplitude of 0.090deg.

With the perturbations from the Earth turned on, if the antenna were at 20deg from the Earth, the differential accelerations due to the Earth would be reduced by a factor of 5 compared with those for LISA. Thus it is of interest to consider the possibility of scheduling periodic orbit correction maneuvers in order to compensate for the differential accelerations due to the Earth, and keep the angle variation amplitudes down to about 0.090deg over the whole mission lifetime.

It will be assumed here that the normal operation of the mission would be interrupted every six days in order to reorient the high gain communications antennas on the three spacecraft and do checks on the optical systems. The necessary orbit corrections would be done at these times using the micro-Newton thrusters. The main drawback would be the loss of a few percent of the science data during the period of the thrusting. The requirements to achieve this will be discussed in the rest of this article.

2. Periodic Thrust Requirements

The orbits currently being considered for an eLISA type mission (ref Danzmann (2012); Stebbins (2012)) are drift-away orbits, where the distance from Earth is increasing with time at a rate of up to 6deg/yr. The initial distance from Earth at the beginning of the commissioning period for the mission would be 9deg or more. As an example, an initial separation of 12deg and a drift rate of 5deg/yr over a 6 yr total mission lifetime will be assumed here. For this case, in comparison with starting 9deg from the Earth and drifting away at 6deg/yr, the extra δV required would be ~ 60 m/s.

From eq. 30 of Sweetser (ref Sweetser (2005b)), the second time derivatives of the arm lengths between spacecraft due to the Earth are given approximately by:

$$\begin{aligned}\ddot{D}_{23} &= \sqrt{3}K [\cos(2L) - 0.5], & \ddot{D}_{12} &= \sqrt{3}K [\cos 2(L - 120 \text{ deg}) - 0.5], \\ \ddot{D}_{31} &= \sqrt{3}K [\cos 2(L + 120 \text{ deg}) - 0.5].\end{aligned}\quad (2)$$

Here $K = GMD/[(\sqrt{3})(S^3)]$, where G is the gravitational constant, M is the mass of the Earth, D is the arm length, and S is the mean distance from the Earth. The eccentricity of the Earth's orbit is neglected. For 12deg from the Earth, $K = 7.5 \times 10^{-9}$ m/s². The geometry for periodic orbit corrections using the micro-Newton thrusters on each spacecraft is shown in Fig. 1. It is assumed that radial and tangential accelerations (R_i, T_i) of the i -th spacecraft with respect to the centre of the triangle can be produced by the thrusters. For the LISA mission, the numbers that have been considered previously for the maximum thrust in each direction range from roughly 30 μN to 150 μN , and we will assume 80 μN here. If the spacecraft mass is roughly 660 kg, this would give a maximum spacecraft acceleration in the radial or transverse direction of 1.2×10^{-7} m/s².

If the thrusters could be used continuously to cancel out the time-varying part of the differential accelerations due to the Earth, the following combination of accelerations due to the thrusters would do what is needed:

$$R_1 = K \cos(2L), \quad R_2 = K \cos 2(L + 120 \text{ deg}), \quad R_3 = K \cos 2(L - 120 \text{ deg}) \quad (3)$$

$$T_1 = K \sin(2L), \quad T_2 = K \sin 2(L + 120 \text{ deg}), \quad T_3 = K \sin 2(L - 120 \text{ deg}). \quad (4)$$

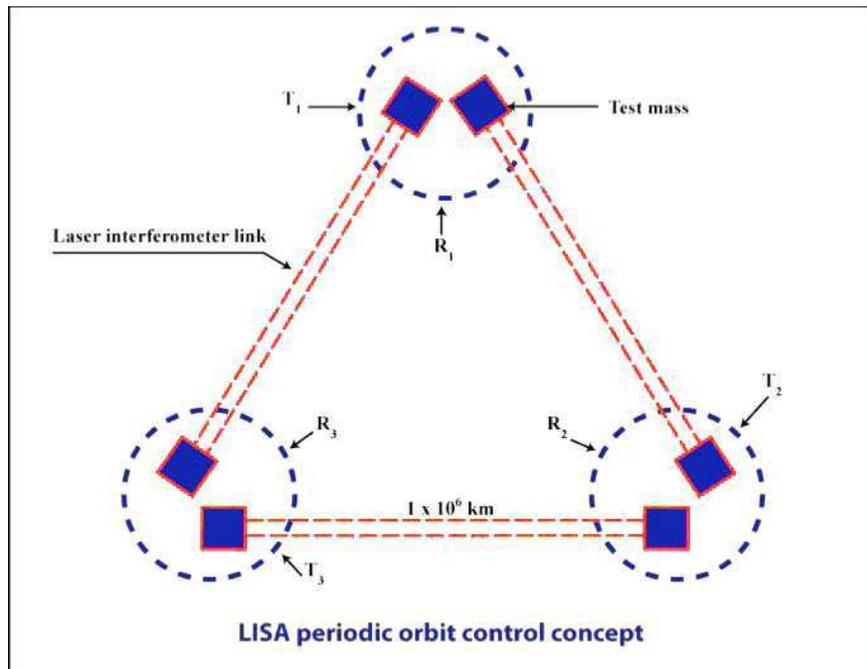


Figure 1. LISA periodic orbit control concept

However, continuous thrusting cannot be used because the resulting acceleration of each spacecraft would have to be applied to the test masses inside it also to keep them centered in their housings. Thus noise in the required forces during regular science operations would be a serious concern, and periodic orbit corrections would be used instead.

Some of the thrust from the micro-Newton thrusters on each spacecraft will be required to cancel out the effect of the solar radiation pressure. Thus it will be assumed here that $70 \mu\text{N}$ is the maximum thrust available in the radial and transverse directions for use in the periodic orbit correction maneuvers. With 660 kg for the spacecraft mass and orbit corrections every six days, the time necessary for the corrections would be 10.2 hr initially at 12deg from the Earth. However, this would be reduced to 6.9 hr at the end of the commissioning period, about four months later. The result would be the loss of 4.8% of the science data. One year later, the required time would be further reduced to 2.7 hr, corresponding to 1.9% loss of the science data.

The Gravitational Reference Sensors on the spacecraft are assumed to be essentially the same as those that have been developed for use on the LISA Pathfinder mission (ref Weise et al. (2008)). To keep each test mass centered in its housing during the orbit correction periods, the maximum voltage needed on the capacitor plates surrounding the test mass would be under 40 volts rms. This is larger than the voltage range provided when the "fine control mode" is being used for the test masses, but well within the range for the "coarse control mode", which is required during initial release of the test masses. The extra acceleration noise that is present during the use of the coarse mode would not be sufficient to interfere with keeping the interferometric links between the spacecraft in nearly normal operation.

3. Advantages of Keeping the Angle Variations Small

For the proposed NGO mission, the expected amplitude of the angle variations at each spacecraft over the six years of nominal plus extended mission lifetime was about 0.8deg. This amplitude was similar to that for the LISA mission. The effect of the shorter baselines was compensated for by the smaller initial distance from the Earth. The mass of the optical assemblies that had to be rotated with respect to a spacecraft was less than for LISA because of the telescope diameter being reduced from 40 cm to 20 cm. However, the optical assembly still had to be locked in place during launch, and to have very small pointing jitter during operation on orbit.

An approach that had been considered earlier for LISA was to keep each telescope fixed with respect to the main spacecraft structure, but to accommodate the required angular motion of the transmitted laser beam by having a small rotating mirror on the optical bench before the telescope that would change the direction of the beam (ref McNamara (2012)). This was called “in-field guiding”. It was regarded as feasible, but requiring careful design and testing in order to prevent slight translational jitter in the effective mirror position from causing noise in measuring changes in the arm length differences between spacecraft.

With the considerably smaller angle variations that would be needed if periodic orbit corrections are planned on and made, it appears that the use of in-field guiding would be quite attractive for an eLISA mission. Careful design and testing of the mirror rotation system still would be needed, but having a considerably smaller rate of angular change to correct for would be a substantial advantage. With in-field guiding plus the expected smaller telescope diameter for eLISA, the reduction in payload complexity would be expected to be significant. And the extra fuel needed for the micro-Newton thrusters used in periodic orbit corrections would be small because of the small duty cycle of the extra thrusting.

One issue to consider, if the in-field guiding range is restricted to plus and minus 0.1deg, or perhaps 0.15deg, is what would happen if the thrusters on one spacecraft lost the capability of providing the assumed level of thrust. This has not been investigated, but it seems likely that other spacecraft could take over the necessary thrusting responsibilities with only a moderate increase in the loss of observing time.

The possibility of applying orbit corrections to the LISA spacecraft in order to keep the effects of the Earth on the triangle geometry from increasing with time was discussed some time ago (ref Bender (2006)) by one of us. However, at the time it was assumed to be sufficient to cancel out the annual averages of the perturbations due to the Earth, and this was incorrect. Canceling out the semi-annual variations in the differential accelerations actually is necessary, so that much higher compensating accelerations would be needed than calculated in Bender (ref Bender (2006)).

4. Conclusions

It appears that planning on including periodic orbit correction maneuvers is worth considering for any eLISA type mission. No modifications to, or additional requirements on, the micro-Newton thrusters are required, and the main expected impact is a reduction of science observation time on the order of a few percent. This approach would make the use of in-field guiding for the spacecraft optical systems considerably simpler, and probably would contribute to reducing the payload mass. Simulations of the expected orbit correction strategy certainly are needed, but preliminary estimates of what would be required are encouraging.

It should be emphasized that the required thrust estimates in this paper are based on a simplified model where the line between the eLISA triangle of spacecraft and the Earth is assumed to be perpendicular to the direction toward the Sun, and the Earth is in a circular orbit. Thus there will be some small components of the differential forces that are perpendicular to the plane of the triangle. However, it is expected that enough out-of-plane thrust capability will be available to counteract such forces.

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