

Possible post-LISA science missions with gravitational reference sensors

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Abstract. Among the many interesting possibilities for types of future missions that would benefit strongly from LISA and LISA Pathfinder technology development, three will be discussed. They are in the fields of fundamental physics, Earth science, and gravitational wave astronomy. The first is a mission to measure the gravitational time delay due to the Sun from a spacecraft near the L-1 point of the Earth-Sun system. It would require gravitational reference sensors (GRSs) with roughly 10^{-13} [10^{-6} Hz/f] $\text{m/s}^2/\sqrt{\text{Hz}}$ performance at frequencies down to about 0.3 microHz. The second type of mission is future drag-free missions to measure time variations in the Earth's gravitational field. One example of such a mission will be described, with two satellites in the same polar orbit at about 300 km altitude. Changes in the roughly 50 km satellite separation would be measured with 10^{-14} or better accuracy, and spurious accelerations of the test masses in the GRS on each satellite would be the other main measurement accuracy limitation. The third mission is a possible moderately improved LISA follow-on mission aimed at being able to detect mergers of 10 solar mass black holes with IMBHs out to redshifts of about 10 in order to investigate the formation and growth of IMBHs in more detail than LISA will be able to achieve.

1. Introduction

There are several possible future missions that have been investigated at least briefly where very low levels of spurious accelerations of test masses are required. Thus the Gravitational Reference Sensor (GRS) results from the LISA Pathfinder mission and LISA will be of major importance for studies of such missions. In order to indicate the scientific opportunities involved and the technical requirements, three particular missions will be described in the following sections. All of these missions also require high-accuracy measurements of changes in light travel times between spacecraft.

2. L-1 gravitational time delay measurement

The gravitational time delay for electromagnetic waves passing near a massive body provides a well known test of general relativity [1]. For waves passing about 1.5 solar radii from the Sun, the round-trip delay can be about 240 microsec. If the measurements are made between two spacecraft that are far from the Sun, the delay depends mainly on the distance b of closest

approach of the wave path to the Sun. The round-trip delay between the spacecraft is given to first order by [2]

$$\Delta\tau = \frac{2GM}{c^3} (1 + \gamma) \ln \left(\frac{r_1 r_2}{b^2} \right).$$

Here M is the mass of the Sun, γ is the PPN "space curvature" parameter, and r_1 and r_2 are the distances from the spacecraft to the Sun.

The most accurate measurement of the gravitational time delay was reported in 2003 by Bertotti, Iess and Tortora [3]. It was based on high-accuracy microwave Doppler measurements between the Earth and the Cassini spacecraft when the line of sight passed close to the Sun. The value of gamma was determined to 2.3×10^{-5} from the measurements.

A number of proposals have been made for missions that could improve the accuracy for the time delay and thus gamma by a large factor. One possibility, presented at conferences in 2005 and 2006, was for optical measurements between a spacecraft near the L-1 point of the Earth-Sun system and a distant transponder spacecraft on a longer period orbit as the line of sight went past the Sun [4,5]. At that time, it was assumed that the time delay would be measured with respect to a cooled cesium hyperfine frequency clock on the L-1 spacecraft, and that the orbit for the distant spacecraft had a 1.5 year period.

The L-1 time delay mission possibility was looked at again recently [6]. It now appears reasonable to assume that the frequency standard in the L-1 spacecraft would be a cooled optical transition clock with $5 \times 10^{-15}/\sqrt{\tau}$ stability out to measurement times τ of 3×10^6 seconds. As an example, this stability has been demonstrated in the laboratory over periods of a few thousand seconds for an optical lattice clock based on the 698 nm line of strontium-87 [7]. The time delay measurements would be made directly on the phase of a laser beam sent to and transponded by the distant spacecraft.

The other main change is that the distant spacecraft is now assumed to be in a 2.0 year period orbit, which gives solar conjunctions 1.0, 3.0, and 5.0 years after launch. In this case, the passages behind the Sun occur right around aphelion for the distant spacecraft, so that the spacecraft temperature is changing only slowly. In addition, the rate of motion of the line of sight with respect to the Sun is increased substantially to 1.9 solar radii per day, compared with 0.7 solar radii/day with the previously assumed orbit. This reduces the drag-free requirements on both spacecraft, as well as the clock stability requirement for a given accuracy for gamma.

For an L-1 time delay mission, the requirements on the spurious accelerations for the test masses in the GRSs in both spacecraft have to be very tight out to periods of about 3×10^6 seconds. In simulations that have been done recently, the assumed requirement has been $1 \times 10^{-13} [10^{-6} \text{ Hz/f}] \text{ m/s}^2/\sqrt{\text{Hz}}$ down to 0.3 microHz. Meeting such a requirement will require careful thermal design of the whole spacecraft, as well as the GRS. However, the LISA Pathfinder Mission and LISA plus

careful thermal modeling can provide the necessary confidence that such requirements can be met.

Simulations are now being done to determine the accuracy for gamma that can be achieved, based on the new assumptions. One factor that is being investigated more carefully than in previous studies is how well orbit corrections for the two spacecraft can be determined simultaneously with gamma from the data. Preliminary simulations indicate that this won't be a substantial limitation, but confirmation of this is needed. If good accuracy for gamma can indeed be achieved, then the scientific value of such a time delay mission appears to be high.

3. Future drag-free missions for mapping time variations in the Earth's gravity field

The GRACE mission that has been flying for over 5 years is making much more accurate measurements of time variations in the Earth's gravity field than were possible previously. Two satellites are in the same nearly polar orbit, separated by about 200 km. Their altitude is roughly 450 km, in order to permit a mission lifetime of about 10 years. Each satellite contains an accelerometer built by ONERA in Paris, to permit correction during the analysis for non-gravitational accelerations. Changes in the satellite separation are measured with roughly micron/second accuracy by a two-frequency millimeter wave interferometric system.

The first US follow-on mission to GRACE is likely to be similar to GRACE, but possibly with a laser interferometric system added as an experiment in order to demonstrate improved capability for measuring changes in the satellite separation. However, the possibility of flying both satellites in a drag-free mode in other future missions has been widely discussed, and is being considered in a number of institutions. Whatever limitation due to spurious accelerations is present in GRACE data can be strongly reduced by drag-free operation. In addition, such missions can be flown at considerably lower altitudes, where the shortest wavelength spatial variations in the Earth's gravity field have not been attenuated as much by upward continuation. The combination of drag-free operation and laser measurements of the satellite separation is attractive, but the extra cost of drag-free operation has to be justified by the additional scientific benefits.

It unfortunately is not known at present how much of the reduction in spurious accelerations possible with the LISA Pathfinder GRS design could be taken advantage of in future GRACE follow-on missions. It takes about 25 days for the ground track of a GRACE-type pair of satellites to cover the Earth with roughly 1 degree separation of the tracks. Such close spacing of the ground tracks is highly desirable, since changes in the water storage in individual river basins is one of the sources of time variations in the gravity field that is of major scientific interest. During the 25 days, time variations in the geoid height anywhere on the Earth tend to get aliased in with the value at the measurement time at a particular place of interest. This non-local aliasing becomes a dominant limitation as the measurement accuracy is improved. The term "non-local" is included in order to distinguish this issue from aliasing due to time variations at a particular location of interest.

A number of studies are being carried out in order to try to understand the limitation due to non-local aliasing. In some of these, two or more pairs of satellites in polar orbits are assumed. An

alternate approach [8], with one pair in a polar orbit and a second pair in a lower inclination orbit, will be discussed briefly below. To permit detailed studies, particular orbits have been chosen for what has been called a Dual-GRACE mission. Altitudes of about 310 km are assumed, along with 62.7 degree inclination for the second pair. A 79 revolution repeat ground track was chosen for the polar pair, and a 360 revolution repeat ground track for the lower inclination pair. The corresponding ground track repeat periods are about 5 days and 23 days.

The presumed advantage of the chosen orbits is that quite dense ground track coverage would be obtained at latitudes within about 29 degrees of the poles. During a 5 day period, the maximum spacing between ground track would be less than 115 km. Thus, in solutions that concentrate mainly on these high latitude regions, time variations with longer than 5 day periods would be resolved. These results then could be used in analyzing the measurements at lower latitudes. The high latitude parts of the 62.7 degree inclination pair ground tracks would provide improved information on the east-west variations in the geoid within 35 degrees of the poles, while the lower inclination of the pair would provide many more orbit crossings at low latitudes than with a second polar pair. Thus, for missions with two pairs of drag-free satellites, having one of the pairs in a non-polar orbit appears to be worth exploring. If the non-local aliasing problem can be reduced substantially by this or some other mission design choice, than the very low spurious acceleration level achievable with GRS type sensors can be taken advantage of in future Earth gravity variation missions.

4. Possible future LISA follow-on mission

It may seem very early to consider possible future gravitational wave missions for after LISA has been flown. However, suggestions have been made for several extremely challenging future missions aimed at detecting a primordial gravitational wave background in the frequency range from 0.1 to 10 Hz. Thus it seems desirable to consider what could be accomplished by a mission with less severe measurement requirements, and what new scientific objectives would justify such a mission.

One such suggestion is for a mission called the Advanced Laser Interferometer Antenna, or ALIA [9]. It would be like LISA, but with a factor 10 shorter arm lengths (500,000 km). The strain measurement accuracy would be a factor 30 better than for LISA. This corresponds to 6×10^{-14} m/ $\sqrt{\text{Hz}}$ above roughly 30 millihertz. Possible choices for design parameters are 1.0 meter telescope diameters and 30 Watts of laser power at 1.064 micron wavelength. Spurious acceleration levels below 3×10^{-16} m/s²/ $\sqrt{\text{Hz}}$ down to about 1 millihertz also would be required.

LISA is expected to observe signals from a considerable number of mergers involving intermediate mass or larger black holes out to redshifts of about 10. The main purpose is to investigate the formation and growth of massive black holes. But LISA won't have enough sensitivity to see 10 solar mass black holes merge with larger ones, except at low redshifts. Since many more mergers of roughly 10 solar mass black holes with intermediate mass black holes (IMBHs) at large redshifts are expected, a mission that could observe such mergers would give much more detailed information on the initial formation and growth of the IMBHs.

In view of the above, there appears to be a strong scientific justification for a LISA follow-on mission with substantially improved sensitivity, but not extremely high sensitivity. Such a mission might be quite different than what is proposed as ALIA. However, the required limit on spurious accelerations is likely to be at least as stringent as for ALIA, and thus additional research beyond the GRS development for the LISA Pathfinder mission and for LISA is expected to be needed. It will be interesting to see if some of the objectives for observing BH-IMBH binary mergers out to large redshifts can be achieved with the intermediate level mission called pre-DEGIGO [10], which is being proposed for study in Japan. This apparently will depend mainly on the arm length and level of GRS performance that are adopted for pre-DECIGO.

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