Gravitational Wave Detection by Laser Interferometry in Space – the Project ASTROD

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Abstract

A Chinese space project ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) is mainly intended for the precise determination of relativistic parameters β, γ, and the solar quadrupole moment J_2. From one spacecraft near the Earth (Lagrange point L1), the apparent distances to two other spacecraft are monitored, at a time when they simultaneously are on the opposite side of the sun (2 AU away). During the travel of these two distant spacecraft to that constellation, the three spacecraft form a triangle that lends itself to gravitational wave (GW) detection. The arm lengths of between 1 and 2 AU allow GW measurement at frequencies even below 10^{-5} Hz, significantly below the range covered by the NASA-ESA project LISA. Events involving supermassive black holes may thus become more reliably detectable. Some of the technological challenges of such a low-frequency GW detection will be discussed, and an estimate of the sensitivity will be advanced.

A technology demonstrator (Mini-ASTROD) is planned, with only one distant spacecraft, and using a dedicated telescope for the earth station. The spacecraft is to be injected into its final orbit via a double fly-by at Venus. Mini-ASTROD is now undergoing a Phase-A study; launch will not be until 2008.

1. Introduction

This third of three talks deals with the space project ASTROD for the detection and measurement of gravitational waves, for more details see [1, 2, 3].

Gravitational wave (GW) astronomy may not be very far from realization. *Ground-based* interferometers are in their final phase of commissioning, and they will cover the frequency range between a few Hz and several kHz. For the spaceborne interferometer of the joint ESA-NASA project LISA (Laser Interferometer Space Antenna), the frequency range is between 10^{-4} Hz and 1 Hz [4]. The space project ASTROD, with base lengths of the order 1 to 2 AU, i.e. 30 to 60 times the arm lengths of LISA, would provide a welcome extension of this frequency range, perhaps down to less than 10^{-5} Hz.

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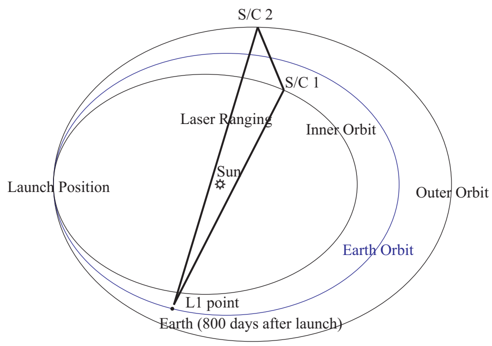

Fig. 1. Orbits of the three ASTROD spacecraft, spacecraft S/C 3 stays near Earth (Lagrange point L1)

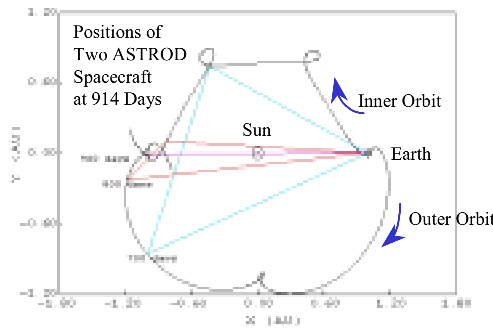

Fig. 2. Relative orbits of the two distant ASTROD spacecraft, with spacecraft S/C 3 fixed near Earth

2. Proposed space project ASTROD

The space project ASTROD [1, 2, 3] is a mission with three spacecraft, all three in solar orbits similar to the Earth's orbit. Figure 1 gives a notion of these three different orbits of the three spacecraft. While the main targets of ASTROD will be the measurement of relativistic effects in the solar environment (β, γ, J_2), an interesting additional application is the measurement of gravitational waves. It is only this latter objective that will be discussed in this paper.

Due to the different orbit parameters, after starting from identical positions, the three spacecraft will drift away from each other, and at times will have constellations resembling the equilateral triangle of LISA, only by a factor 50 or so bigger, as indicated in Figure 2, dashed lines. This larger armlength will make ASTROD particularly useful at extremely low frequencies.

The detection principle in ASTROD will be modelled after that of LISA: test masses in sensors will be the references for the interferometric measurement of changes in distance. In the design of these sensors, the ASTROD project will be able to draw from the experience gained in the 'LISA Technology Package' LTP (to fly in 2006) and then later in LISA proper (2011).

2.1. ASTROD sensitivity

So far, no dedicated study of the ASTROD sensitivity has been made. Rather, the plot to be presented here, as well as the ones published in [4], are based on extrapolations from the LISA sensitivity curves, as given in [5]. Such an extrapolation, based on current LISA technology, is presented in Figure 3.

In the sensitivity as measured in strain $h \sim \Delta L/L$, the longer arm length of ASTROD is favorable, as one divides by an optical path L that is by a factor 30 to 60 larger. But this rule has to be treated separately for the three noise regimes corresponding to the three shaded areas in the LISA sensitivity plot given in [5].

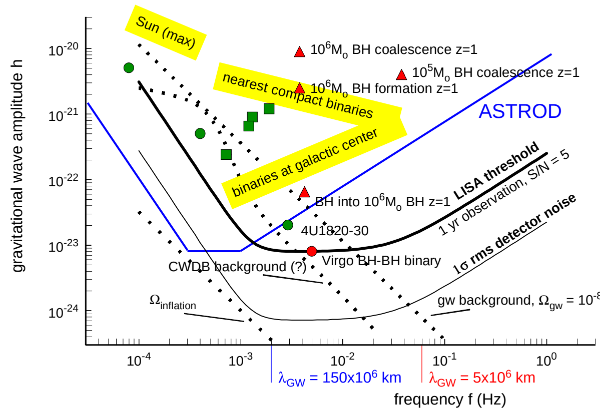

Fig. 3. Sensitivity of ASTROD: the straight solid lines "ASTROD" are inserted in the LISA sensitivity drawing of [5]. Sensitivity with SNR = 5, and averaging over all angles of incidence and polarization, and over one year of observation time.

The flat region The white-noise part, where the sensitivity is practically frequency-independent, would remain at the same strain level, as the higher value of the arm length L is compensated by the loss in light power by $1/L^2$.

The antenna response region The rise on the right-hand side also results from the (white) shot noise, taking into account the reduced response to actual GW signals, which rolls off roughly as Λ_{GW}/L, once the optical path L exceeds $\Lambda_{\mathrm{GW}}/2$. Thus the rise in the noise curve sets in at lower frequencies.

The acceleration noise region The longer arm length will also reduce all acceleration-induced noises (at the low frequency side) by just this factor of length increase. So it can be extrapolated from the LISA curve by an appropriate, length-proportional shift downwards, i.e. to lower noise levels.

This estimate, based on LISA technology of today, would lead to a sensitivity as sketched roughly by the three straight lines "ASTROD" in Figure 3.

It is hoped that by the time of building ASTROD, some further progress in the noise reduction in the sensors can be made, and that the limiting left-hand line can then be pushed further to the left, to lower frequencies, as shown in [1, 2].

2.2. Challenges in ASTROD

Even though in some respects ASTROD will be modelled after LISA, there will be various details where the technological requirements are much more challenging.

Low-power interferometry Whereas LISA had powers available in the order of 10^{-10} W, ASTROD will have only 3×10^{-14} W. To do interferometry with such low powers will be an important issue. Progress in the 'art' of low-power detection is being made [7] and again the LISA project will point the way, but the ASTROD situation is by orders of magnitude more challenging.

Inclination to sun Through their entire lifetime the LISA spacecraft will have a constant inclination to the sun of 30°. The ASTROD spacecraft will not have such a favorable constant inclination, and more elaborate thermal shielding will be required to maintain a similarly benign environment for the sensor.

Direct sun light The LISA inclination prevents direct light from the sun entering the sensitive optical detector. For ASTROD, on the other hand, the measurements of the relativistic effects requires light paths that pass very close to the sun. Only with elaborate coronograph systems will these measurements be possible. The GW measurements will, however, be made at times when the ASTROD telescopes will not point close to the sun, so then the problem is reduced.

Constancy of arm lengths The processing techniques [8] required for LISA to cancel out fluctuations in laser frequency and position of the test mass inside the sensor will also have to be applied in the case of ASTROD. In LISA, the application is relatively easy, as the arm lengths are rather well constant throughout the course of the year. For ASTROD, the arm lengths change much more rapidly, and by much larger amounts. So an increased effort has to be made to render the LISA data-analysis routines applicable also under these more challenging conditions. The case of grossly unequal arms is treated in [9].

3. Conclusion

Recent understanding of the very violent events between colliding galaxies makes measurements at even lower frequencies than accessible for LISA a very desirable goal. With dimensions as envisaged for ASTROD one has improved chances of seeing such events in the light of gravitational waves. That could make ASTROD a logical extension of the – so far – much more progressed mission LISA.

References

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