A Possible Laser Gravitational Wave Experiment in Space

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An investigation has been started of possible designs for a laser gravitational wave experiment with baseline lengths of roughly 10⁶ km or longer. The objectives of the experiment are to search for narrow-band signals with periods of seconds to hours, for pulses of gravitational waves, and for broadband background radiation. One of the main goals is to detect signals from known rotating binary systems, such as Am CVn, WZ Sge, and i Boö. The corresponding gravitational wave periods are 8.7, 40.5, and 198 minutes. The expected strain amplitudes are roughly 0.4, 0.5, and 6 × 10⁻¹², respectively, which correspond to equivalent accelerations of 50, 4, and 2 × 10⁻¹⁹ g for a 10⁶ km baseline. The uncertainties in the expected signal strengths comes from the uncertainty in the distances. In view of the extremely tiny equivalent accelerations, care will be needed in designing the experiment in order to minimize spurious accelerations due to forces other than the gravitational attraction of the sun and planetary bodies.

The first approach considered [1] was to make laser heterodyne distance measurements over two non-parallel baselines which remain equal in length to 10⁻⁵ over the duration of a single experiment. For a laser stability in a 1 cycle/h bandwidth of 5 × 10⁻¹⁴ or better, periodic changes in the difference in length of the two baselines could be measured with roughly 10⁻²² sensitivity in one day. Three spacecraft equipped with laser transmitters and receivers are required. The laser beams would be sent both ways over each baseline, and the beat signals detected at each end. With 10 mW of transmitted laser power in the visible from each satellite, the required diameter of the optical systems is 50 cm.

One geometry considered was to have a central spacecraft at the L1 (or L2) libration point of the earth-sun system, which is about 10⁹ km from the earth, and the other two spacecraft 1.5 × 10⁶ km away at the L4 and L5 libration points. It is feasible to arrange the initial conditions so that the baselines from the central spacecraft to the other two stay equal to 10⁻⁸ over moderately long times. However, the number of signal counts detected per second would be quite low, and the propulsion capability necessary to reach the L4 and L5 libration points in one year is substantial.

A second geometry discussed involved putting two spacecraft about 1.4 × 10⁶ km apart in coplanar one year period circular orbits around the sun, which define a reference plane, and the third spacecraft in a similar orbit with a phase difference of about 0.3 degrees with respect to the reference plane [2]. With proper phasing of the orbital positions, the third spacecraft will be near the highest point above the reference plane when the other spacecraft are equally far ahead of and behind it. The distances from the third spacecraft to the other two would be 10⁶ km, and would stay equal to 10⁻⁸ over roughly a day. With this separation the signal to noise would be high enough so that the lasers in the first two spacecraft could be phase locked to the signals arriving from the third spacecraft. However, thrusts would have to be applied to the third spacecraft about every day in order to reestablish the proper geometry.

Another approach which we would like to suggest is to let the two baselines differ in length by up to perhaps one part in 10⁶, but measure the apparent changes in the length L of one baseline as well as the changes in the difference in length ΔL. The differences between the measured apparent changes in the baseline length L with periods of seconds to hours and those expected from celestial mechanics would be used to determine the laser frequency variations. This additional information makes it possible to correct for the laser frequency variations in determining whether changes in ΔL occur due to gravitational waves. The only restriction in interpreting the results is the implicit assumption that the change in L due to the gravitational waves is not orders of magnitude larger than the change in ΔL.

With the new approach, we are exploring a different geometrical arrangement with 10⁶ km spacecraft separations which would allow the experiment to run for long periods of time without orbit corrections. The main spacecraft would be placed in a 1 year period circular orbit, which defines the reference plane. The other two spacecraft would be placed in orbits with inclinations e = 1/300 and inclinations with respect to the reference plane of very nearly √3 e. By proper phasing, the other spacecraft will appear to rotate about the main spacecraft with an annual period in a plane whose normal is tipped downward by 30 degrees with respect to the direction toward the sun.

The most difficult design problem for the proposed gravitational wave experiment probably will be shielding out or compensating for perturbing forces on the spacecraft due to fluctuations in the solar wind pressure and other effects. The magnitude of the fluctuating accelerations at the frequencies of interest will be roughly 10⁻⁸ g. A disturbance compensation system (DISCOS) which reduced perturbations from roughly 10⁻⁸ g to 5 × 10⁻¹² g even at zero frequency was flown on the TRIAD satellite in 1972. Initial studies indicate that an improved DISCOS can be designed which would reduce spurious accelerations at the frequencies of interest to the necessary level in a 1 cycle/h bandwidth of less than 10⁻¹⁸ g. However, attention will have to be placed on avoiding the many sources of perturbations in such systems.

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1In this context, the gravitational acceleration at the earth's surface g, is used as a unit of acceleration.
References
