LASER GRAVITATIONAL WAVE EXPERIMENT IN SPACE

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Detection of gravitational radiation is an important research goal in physics and astrophysics. At the Joint Institute for Laboratory Astrophysics, an investigation is being carried out of possible designs for a laser gravitational wave experiment using free masses and baseline lengths of $10^6$ km or longer.

During the past several years, the question of a laser-based gravitational wave experiment in space has been under active discussion at JILA. Our long-range goal is to establish the feasibility of, and to participate in, a space experiment designed to detect gravitational waves, including particularly those believed to be emitted during the formation of massive condensed objects in galaxies. In addition to studying stellar collapse as well as neutron stars and black hole formation, the proposed experiment would search for narrow-band signals with periods of seconds to hours, for pulses of gravitational waves, and for broadband background radiation. One of the goals would be to detect signals from known rotating binary stars such as Am CVn, WZ Sge, and 1 Boo. The corresponding gravitational wave periods are 8.76, 40.5, and 193 minutes; and the expected strain amplitudes are roughly 0.4, 0.5, and $6 \times 10^{-21}$, respectively, corresponding to equivalent accelerations of 50, 4, and $2 \times 10^{-19}$ g for a $10^6$ km baseline. The main uncertainty in the expected signal strengths comes from the uncertainty in the distances. In view of the extremely tiny equivalent accelerations, great 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 we considered [1] was to make laser heterodyne distance measurements over two non-parallel baselines which remain equal in length to $10^{-8}$ over the duration of a single experiment. For a laser stability in one cycle per hour bandwidth of $5 \times 10^{-14}$ or better, periodic changes in the difference in length of the two baselines could be measured

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with roughly $10^{-22}$ sensitivity in one day. Three spacecraft equipped with laser transmitters and receivers would be 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 $10^6$ km from the earth, and the other two spacecraft $1.5 \times 10^8$ 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 we have discussed involves putting two spacecraft about $1.4 \times 10^6$ 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 which is inclined by 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 $10^6$ 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 possibility is to let the two baselines differ in length by up to perhaps one part in $10^3$, but measure the apparent changes in the length L of one baseline as well as the changes in the difference in length $\Delta L$. 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 $\Delta L$ 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 $\Delta L$. 
With this approach we are exploring a different geometrical arrangement with $10^6$ 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 yr period circular orbit, which defines the reference plane. The other two spacecraft would be placed in orbits with eccentricities $e = 1/300$ and inclinations with respect to the reference plane of very nearly $\sqrt{3}$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 $30^\circ$ with respect to the direction toward the sun.

Our most recent efforts are focused on studies of the effect of short period laser noise on the proposed laser gravitational wave experiments -- the conclusions of which will have an important influence on determining the laser stabilization requirements for the experiment. Studies relevant to this point are being made of the degree of stabilization that can be achieved by locking a visible laser to a temperature-controlled and mechanically-isolated Fabry-Perot type of cavity.

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 $10^{-13}$ g. A Disturbance Compensation System (DISCOS) which reduced perturbations from roughly $10^{-8}$ g to $5 \times 10^{-12}$ 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, careful attention will have to be given to avoiding the many sources of perturbations in such systems.

References
