Long baseline gravitational wave detectors - status and developments

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Abstract. Results are now appearing from the first generation of long baseline gravitational wave detectors - LIGO, VIRGO, GEO 600 and TAMA 300 - that use laser interferometry for motion sensing. In this short review the current state of the field will be briefly discussed, and the prospects and plans for future instruments will be outlined.

1. Introduction
Predicted by general relativity to be produced by the acceleration of mass, gravitational waves have remained an enigma since 1917. However, after 35 years of experimental research we are rapidly approaching the point at which gravitational waves from astrophysical sources may be directly detected by the long-baseline detectors LIGO (USA), GEO 600 (Germany/UK), VIRGO (Italy/France) and TAMA 300 (Japan) which are now in or coming into operation.

Detection will allow us to start looking into the heart of some of the most violent events in the Universe. A full discussion may be found in [1].

2. Gravitational waves
From an experimentalist’s point of view gravitational waves are best thought of as fluctuating strains in space-time.

Gravitational wave signals are expected over a wide range of frequencies; from $10^{-17}$ Hz in the case of ripples in the cosmological background to $10^{17}$ Hz from the formation of neutron stars in supernova explosions. The most predictable sources are binary star systems. However there are many sources of much greater astrophysical interest associated with black hole interactions and coalescences, neutron star coalescences, low-mass X-ray binaries such as Sco-X1, stellar collapses to neutron stars and black holes (supernova explosions), rotating asymmetric neutron stars such as pulsars, and the physics of the early Universe. The signals from all these sources are at a level where detectors of very high strain sensitivity – of the order of $10^{-23}$ over relevant timescales – will be eventually required to allow a full range of observations and such detectors may be on ground or in space.
3. Long Baseline Interferometric Detectors

There are currently in operation, or in final stages of commissioning, a network of gravitational wave detectors each of which is based on using laser interferometric sensing to detect the changes, induced by gravitational waves, in the relative arm lengths of large-scale variants of Michelson-type interferometers, where the arms are formed between freely-hung mirrors.

The American LIGO project [2] comprises two detector systems with arms of 4 km length, one in Hanford, Washington State), and one in Livingston, Louisiana. One half length, 2 km, interferometer has also been built inside the same evacuated enclosure at Hanford. Construction of LIGO began in 1996 and progress has been outstanding with operation at instrumental design sensitivity now having been achieved as is indicated in figure 1.

The French/Italian VIRGO detector [3] of 3 km arm length at Cascina near Pisa, as shown in figure 2, is close to completing commissioning and the Japanese TAMA 300 detector [4], which has arms of length 300 m, is operating at the Tokyo Astronomical Observatory.

All the systems mentioned above are designed to use resonant cavities in the arms of the detectors and use standard wire sling techniques for suspending the test masses.

However the German/British detector, GEO 600 [5], is somewhat different. It makes use of a four pass delay line system with an advanced optical signal enhancement technique known as signal recycling, utilises very low loss fused silica suspensions for the test masses, and is expected to reach a sensitivity at frequencies above a few hundred Hz close to those of VIRGO and LIGO when they are in initial operation.

![Strain Sensitivity for the LIGO 4km Interferometers](image)

**Figure 1.** Amplitude spectral density of the noise from the LIGO detectors compared with the design goal. (Courtesy of LIGO).
GEO is now fully built and its sensitivity is being continuously improved. Currently it is within a factor of approximately 3 of design sensitivity over a significant fraction of its frequency range.

Four science runs have so far been completed with these new interferometric detectors. All have involved the LIGO detectors, three have involved the GEO detector and two had TAMA involvement.

New ‘upper limits’ have been set on the strength of gravitational waves from a range of source: coalescing compact binaries, pulsars, burst sources and a stochastic background of gravitational waves and these will be discussed briefly in the next talk [6]. The fifth science run of the LIGO detectors started on 4th Nov 2005 and is currently ongoing with GEO having joined in January 2006. This run, expected to last about 18 months, will be the longest stretch of data taking to date.

During the next few years we can expect to see searches for gravitational wave signals at a sensitivity level where a detection could be made. Recent discoveries of additional compact binary systems have improved the statistics for the expected rate of binary coalescences detectable by the LIGO system by a significant factor, giving a plausible upper limit of approximately 1 per 3 years for binary neutron star coalescences and approximately 1 per year for binary black hole coalescences [7].

However detection at the current level of sensitivity of the initial detectors is no way guaranteed; thus improvement of the order of a factor of 10 in sensitivity of the current interferometric detectors is needed to reach sensitivity levels where many signals are expected.

Thus plans for an upgraded LIGO, Advanced LIGO, are already well formed. Advanced LIGO will incorporate 40 kg fused silica test mass mirrors, suspended by fused silica fibers or ribbons, along with an improved seismic isolation system, and increased laser power, close to 200 W. The upgrade is expected to commence in 2010, with full installation and initial operation of the upgraded system by 2014. On approximately the same timescale we can expect to see a similar upgrade to VIRGO, the rebuilding of GEO as a detector aiming at high sensitivity in the kHz frequency region and the building of a long-baseline underground detector, LCGT [8], in Japan. To go beyond this point, however, a number of challenges involving mechanical losses in coatings, thermal loading effects, and the use of non-classical light to bypass the standard quantum limit will have to be met. Cryogenic test mirrors, and non-transmissive optics [9], are likely to be adopted, using materials of high thermal conductivity such as silicon.

Thus research groups in the field are already looking towards the next generation of ground-based detectors while being actively involved in research towards the space-borne detector LISA, the Laser Interferometer Space Antenna [10] illustrated in figure 3.

Figure 2. Birds eye view of the VIRGO detector site at Cascina in Italy (courtesy of the VIRGO Project) and b) the GEO 600 detector near Hannover (courtesy of the GEO Project).
4. Long baseline detectors in space
Perhaps the most interesting gravitational wave signals (those resulting from the formation and coalescence of black holes in the range $10^3$ to $10^6$ solar masses) will lie in the region of $10^{-4}$ Hz to $10^{-1}$ Hz, and a detector whose strain sensitivity is approximately $10^{-23}$ over relevant timescales is required to search for these. The most promising way of looking for such signals is to fly a laser interferometer in space. LISA is being proposed by an American/European team; it consists of an array of three drag-free spacecraft at the vertices of an equilateral triangle of length of side $5 \times 10^6$ km. This cluster is placed in an Earth-like orbit at a distance of 1 AU from the Sun, and 20 degrees behind the Earth. Proof masses inside the spacecraft (two in each spacecraft) form the end points of three separate but not independent interferometers. LISA is expected to be launched in 2015 or shortly thereafter and to be producing data for up to ten years. A demonstrator mission, LISA Pathfinder, is in phase C/D of development and hardware is being built for a launch in late 2009.

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