# GEO 600

## A 600 m Laser Interferometric Gravitational Wave Antenna

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### Abstract

This report is largely based on a proposal for a gravitational wave detector with 600 m arms, to be built in Hannover by a collaboration involving the University of Hannover, the Max-Planck-Institut für Quantenoptik (MPQ) at Garching, the University of Glasgow and the University of Wales, College of Cardiff [1].

The detector will incorporate a four-pass optical delay line, and power recycling and signal recycling will be used. Illumination will be provided at 1.06 $\mu$m by a Nd:YAG laser operating at a power of up to 10 W. The test masses will be suspended as double pendulums using fused silica fibres, and isolation will be provided by antivibration stacks.

The civil engineering work will be undertaken under the direction of Hannover, the vacuum system will be constructed by Hannover with assistance from Rutherford Appleton Laboratory, the technology will be developed by Hannover, MPQ and Glasgow working in close collaboration; theoretical input on astrophysical matters and the development of data analysis techniques and algorithms will be undertaken at the University of Wales.

# 1. Introduction

The detection and study of gravitational radiation will be of great scientific importance. It will open up a new window on the Universe through which may come unique information about a variety of astrophysical systems – supernovae explosions, pulsars and coalescing compact binary stars. It is also possible that totally unexpected discoveries will be made, in much the same way as has occurred in radio and x-ray astronomy. Detection will allow direct tests of some aspects of general relativity, which should help to distinguish between rival relativistic theories of gravity.

Many years of development work on prototype detectors, mainly in Germany, the UK and the USA, have produced insight in the relevant noise sources and how to overcome them in the quest for yet higher sensitivities in full-sized detectors. These studies gave rise to a number of technological spin-offs and have been of considerable interest to the general public.

Following these developments and intensive feasibility studies, three large detector systems have been funded worldwide. Two of these – forming the LIGO project [2] will be in the USA, one situated in Washington State and the other in Louisiana; both detectors are to have arm lengths of 4 km. The other funded project – the French/Italian VIRGO project [3] – will have arms of length 3 km and is to be built near Pisa. These instruments are expected to be operational in their initial configuration in about six years' time. Development work is also being undertaken in Japan (100 m prototype) and Australia, in both countries with the long term goal of constructing detectors of 3 km arm length.

The original German-British project [4] – later known as GEO – proposed and agreed in principle in the UK in 1990, and ranking high in the list of projects to be funded in Germany, was cancelled in 1991 due to lack of funding in both countries.

In this paper we discuss a new advanced detector project of 600 m arm length – GEO 600. The detector [1], a four-pass delay line system, with power and signal recycling, should have a sensitivity close to those expected for the first LIGO and VIRGO interferometers, over part of their frequency range.

# 2. Astrophysical aims

## 2.1. Long-term aims

The overall target of all the gravitational wave detector projects is the detection and study of gravitational wave fluxes and waveforms from various astronomical sources. The strength of a gravitational wave signal can be characterised by the strain in space at a detector, the gravitational wave amplitude $h$ being defined as twice this strain.

For example, observations over a year of coalescing binary systems of neutron stars or black holes with a detector capable of detecting bursts with an amplitude of around $10^{-22}$ would provide crucial information about neutron star masses and binary evolution. If three or more detectors see such an event, its location on the sky and its distance can be measured, allowing a high-accuracy determination of the Hubble constant [5], and giving definitive information about whether gamma-ray bursts originate in such binaries. If *four* detectors see an event, this would allow the spin 2 nature of the graviton to be definitively checked. Optical and gravitational observations of a supernova could allow the relative speed of gravitational waves and light to be tested to approximately 1 part in $10^9$. Cross-correlations between two detectors would either detect background stochastic gravitational waves or decrease by 5 orders of magnitude the current upper limit on their energy density. This could put tight constraints on theories of galaxy formation. Pulsars could be searched for by integrating over times of several months, and one might expect one or more detectable pulsars in our galaxy today if 1% of all neutron stars were born with rotation periods of 2 ms or less, and with symmetries allowed by current theory and observation. The recent detection of a 2.1 ms pulsar in SN 1987A suggests that this is a relatively conservative estimate. Moreover, the pulsar PSR J0437-4715 discovered in 1993, at a distance of 100 pc and having a rotation frequency of approximately 173 Hz, could be expected to produce a signal of amplitude up to $3\times10^{-26}$ at $\sim 346$ Hz. Similar techniques might detect a rapidly spinning neutron star rotating at the Chandrasekhar-Friedman-Schutz (CFS) instability point.

### 2.2. Immediate detection aims

The present paper addresses the development of detectors to the sensitivity that is called "Stage-1" by LIGO, roughly the ability to detect a 1 kHz burst with a sensitivity of $10^{-21}$. If the proposed detector is built, then with the two LIGO and one VIRGO first-stage detectors there will be a network of 4 such detectors of comparable sensitivity around the world. Although source predictions at this level are less certain than at the level of $10^{-22}$ that was assumed in the previous section, there are some very exciting possibilities.

Interestingly, since the time the original GEO/LIGO/VIRGO proposals were written some five years ago, a number of astrophysical developments have made strong gravitational waves seem much more likely for some sources.

### 2.3. Some possible target sources

Sources that could be targeted by the network of 4 detectors include:

**Strong bursts from supernovae.** It is increasingly clear that there is a large variety of supernovae, and many low-luminosity ones (like SN 1987A) are missed in surrounding galaxies. Computer simulations are still not able to predict realistically what will happen in a gravitational collapse with high angular momentum, which is the situation likely to lead to gravitational radiation. Until recently, the assumption has been that rotation was not important: all young pulsars, like the Crab, are relatively slowly rotating.

However, the unpublished observations by Middleditch *et al.* [6] of a 467 Hz optical pulsar in SN 1987A, spinning down on a time-scale less than $10^5$ yr, show that, contrary to this prejudice, rapid rotation may be common or even normal [7] in gravitational collapse. The rapid spin may be associated with the unusually low optical brightness of this supernova, and may indicate that a substantial population of supernovae with rapidly rotating cores has been missed in supernova statistics. This would greatly increase the likelihood of strong bursts of gravitational waves, detectable even if they came from the Virgo Cluster by first-stage detectors. The event rate could quite plausibly be several per year.

Moreover, pulsar evidence [8] now suggests that the mean space velocity of pulsars is three times higher than had previously been estimated: typical speeds are 450 km/s. This linear velocity must come from some non-axisymmetric asymmetry in the gravitational collapse, and this would also enhance one's expectations of gravitational radiation. If this velocity is acquired on the timescale of the bounce, 1 ms, then the *minimum* amplitude of gravitational radiation would be about $5\times10^{-21}$ for a supernova at 1 kpc. Of course, if the collapse is messy and non-symmetric, the radiation would be expected to be much stronger than this.

**Coalescing binary systems.** Observations of pulsars like the Hulse-Taylor pulsar PSR 1913+16 have suggested that the nearest such system that will actually coalesce within any year will be about 100 Mpc away. This would be easily detectable by the Stage-2 detectors, with their higher sensitivity and (importantly) better performance at low frequencies; but until recently such events seemed out of the reach of first-stage detectors. However, theoretical studies of binary evolution [9, 10] have recently suggested that there should be a large population of very tight neutron-star binaries that have such short gravitational-wave-inspiral times. The times are so short that the chances of seeing one at any particular time in our Galaxy are small, but the coalescence rate integrated over time in our Galaxy could be at least 100 times larger than before. That would move the nearest such coalescence in one year in to about the distance of the Virgo Cluster, where it might well be detectable by Stage-1 detectors, including GEO 600.

**Pulsars and accreting neutron stars.** If the newly discovered nearby pulsar, PSR J0437-4715, radiates gravitational energy at a rate comparable to the rate at which it is losing rotational energy (as inferred from its spindown), then it would produce a signal of amplitude up to $3\times10^{-26}$ at 346 Hz. This should be detectable by GEO 600 in a year of observing. Significantly, the new pulsar in SN 1987A is spinning down much more rapidly, and would radiate at $h\sim1.4\times10^{-26}$ at 934 Hz on the same assumption; this might also be detectable. In the case of SN 1987A, the assumption that the radiation of gravitational waves is the dominant energy loss is not unreasonable: the magnetic field may well be weak at present, and there could still be significant irregularities in the shape of the star if it were formed in a rapidly rotating collapse. Moreover, the SN 1987A pulsar also raises the possibility that there are nearer pulsars, formed by weak supernovae in our Galaxy, that could still be strong radiators. These might be found by doing wide-band gravitational-wave searches of particular regions of the galactic plane in a year-long data set.

**Stochastic background.** The detection of a cosmological background of gravitational waves would be one of the most significant events in astrophysics since the detection of the cosmic microwave background. There have been no recent developments to suggest that the cosmological gravitational wave background at frequencies above 100 Hz should be any larger than we estimated in the original GEO proposal in 1989. However, searches will certainly be made with Stage-1 detectors, and it is likely that GEO 600 will be able to do a better job with the VIRGO detector than the two LIGO detectors could do at Stage-1. The reason is proximity: to get a good correlation, detectors should be as close together as possible, so that they respond to the same (random) gravitational waves at the same time. The separation of the two LIGO detectors is more than 3 times greater than the separation of GEO 600 and VIRGO, leading to the loss of a factor of about 10 in sensitivity to energy density. It is unlikely that at Stage-1 the LIGO detectors could completely overcome this disadvantage with improved sensitivity or wider bandwidth.

The two European detectors will be likely to set limits on the ratio $\Omega_{gw}$, of the energy density of the gravitational wave background to the closure density, of around $10^{-6}$ at 300 Hz. This is comparable to limits set at very low frequencies (sub-$\mu$Hz) by observations of millisecond pulsars, and will allow the testing of some of the predictions of cosmic string theory.

**Tests of gravitation theory.** The direct detection of gravitational waves will, of course, be a momentous event in physics, and GEO 600 could well allow Germany and the UK to be part of it. But beyond this, the observation of gravitational waves provides significant information about gravitation theory. If a supernova in VIRGO is detected, then the delay between the arrival of the gravitational waves and the light signal tests the speed of gravitational waves. The light should lag behind the gravitational radiation by no more than about 1 day, due to the propagation of the shock in the star. This uncertainty, over a travel time of about 60 Myr, tests the relative speeds to one part in $10^9$ or better.

Another fundamental aspect of gravity research is the question of polarisations other than those predicted by general relativity. These would indicate other spin fields, such as scalar fields, which have lately been the subject of renewed speculation from the point of view of unified field theories involving gravitation. Present limits on the couplings of other fields are about $10^{-3}$ of standard gravity. A gravitational wave observed by *four* detectors would have enough redundant information to provide an independent test of these couplings. *Without GEO 600, there is little prospect that such a test can be performed.* If the source were strong enough, such as a gravitational collapse in our galaxy, then it would be possible to improve present limits on additional gravitational fields.

### 2.4. Future developments

Exciting as some of these possibilities are, it must be stressed that, at the sensitivity levels of initial experiments, detection of gravitational wave signals cannot be guaranteed. Therefore, a further valuable aspect of the 600 m detector would be its use as a development system for later, more sensitive detectors. It is possible that the 600 m detector could have its sensitivity, particularly for narrow band sources, considerably enhanced by cooling of the detector test masses to reduce thermal noise and by optimising the design of the laser interferometry used. The initial design of system will allow for such later developments.

## 3. Required detector performance

To achieve all the detection aims mentioned above, a sensitivity of $10^{-22}$ over a bandwidth of approximately 1 kHz, or a sensitivity spectral density of $3\times10^{-24}/\sqrt{\mathrm{Hz}}$ from about 100 Hz is likely to be required; however the initial aims of the LIGO and VIRGO detectors are somewhat more modest than this - a few times $10^{-23}/\sqrt{\mathrm{Hz}}$. Initial coincidence experiments, likely to last several years around the end of the century are proposed to be at this level. Increasing the sensitivity will require the development of more advanced detectors and at present this is planned as a second stage for both LIGO and VIRGO requiring further development work to be funded.

We believe that a detector with shorter arm length (600 m) using more advanced techniques than are currently proposed for LIGO or VIRGO could achieve a sensitivity close to their initial sensitivities (at least above 200 Hz and possibly within a limited bandwidth) and on a timescale similar to or somewhat earlier than these detectors. The modest scale of GEO 600 will make it easier to introduce the sophisticated technology required. The building of such an instrument could allow a more sensitive coincidence experiment to be carried out in the early stages of operation of the long detectors. Furthermore such a detector could by itself carry out a meaningful search for gravitational radiation from nearby pulsars.

The design of interferometer developed for GEO 600 would be a very strong candidate for installation in the LIGO and VIRGO instruments at a later stage to allow these systems to attain their advanced target performance.

## 4. Proposed joint German/British 600 m detector – GEO 600

Based on many years of development work and collaborative efforts at the University of Glasgow and the Max-Planck-Institut für Quantenoptik, with strong theoretical support from the University of Wales (Cardiff), the research groups in Hannover, Garching, Glasgow and Cardiff are jointly proposing to build a gravitational wave detector using laser interferometry to sense the motion of essentially free test masses which form two perpendicular arms of length 600 m. This instrument will be built on farmland owned by the University of Hannover and available immediately for this purpose. The detector will be built just below ground.

### 4.1. Vacuum system

The vacuum system designed by J.R.J. Bennett from RAL will consist of a cluster of up to 9 stainless steel vacuum tanks each of 1 m diameter at the centre of the system and one tank of the same diameter at each end of the perpendicular arms. The end tanks will be joined to the cluster at the middle by stainless steel vacuum pipes of 0.6 m diameter. The system will be pumped by a combination of turbo molecular pumps and NEG pumps. The design will provide a vacuum pressure close to $10^{-8}$ mbar for $H_2$ and $10^{-9}$ mbar for other heavier gases, this being adequate for the design sensitivity of the instrument.

### 4.2. Interferometer arrangement

Various optical schemes for the interferometer are possible. However, at present it seems likely that a delay line interferometer with four passes in each arm will be installed, as a somewhat simplified version of the original delay line interferometer [4] proposed for the 3 km GEO detector.

Power recycling will be implemented to allow a standing power at the beamsplitter of approximately 6 kW, a figure consistent with the need to avoid excessive distortion of the optical phase fronts due to heating effects mainly in the beamsplitter (based on Winkler *et al.* 1993 [11]). Signal recycling as proposed by Meers (1988) [12] and demonstrated experimentally by Strain and Meers (1991) [13] will be used to increase the storage time of the system for the signal sidebands and so increase the detected signal size in the interferometer.

The input laser power will be approximately 5 W from a stabilised all-solid-state diode-pumped Nd:YAG laser system currently being developed at the Laser Zentrum Hannover (Golla *et al.* 1994 [14]). The excess noise due to relaxation oscillations in such lasers and its relevance for gravitational wave detectors has been studied by Campbell *et al.* (1992) [15] and the necessary reduction in such noise by electronic feedback has been demonstrated by Rowan *et al.* (1994) [16] and by Harb *et al.* [17]. The laser will be frequency prestabilised to a small optical cavity. The main beam will have its direction, beam diameter and convergence stabilised by passing through two in-line mode cleaning cavities of the type originally proposed and implemented by Rüdiger *et al.* (1981) [18]. The interferometer will be locked on a null fringe using techniques partly outlined in the original German/British proposal [4] and taken further in an experimental demonstration on a table top by Strain [13]. These locking techniques are currently being implemented in the suspended-mass 30 m prototype at Garching.

It should be noted that this optical system makes full use of the very low-loss mirror coatings and specially developed low absorption fused silica substrates that are now available. Achieving the required signal storage time with only a small number of bounces and a high degree of signal recycling has advantages over a conventional design, because it gives the detector tunability for narrowband sources and makes it highly immune to optical aberrations [19].

The beamsplitter, and the test masses that form the main mirrors of the interferometer, will consist of solid cylinders of fused silica, approximately 25 cm diameter and 15 cm thickness, with supersmooth and dielectrically coated surfaces. The recycling mirrors will be similar. The coatings will be of laser gyro quality, resulting in optical losses of only a few parts per million.

### 4.3. Seismic isolation, position and orientation control of test mass

The test masses in the interferometer will be isolated from ground motions using a multilayer stack of heavy metal and neoprene or silicone rubber. In order to prevent contamination of the mirror surfaces by impurities it is important that only a negligible surface area of rubber is exposed to the vacuum system. The rubber will therefore be encapsulated in very soft metal bellows which will be pumped separately from the rest of the system. Each test mass, the beamsplitter, and each recycling mirror will be suspended on a double loop as the lower mass of a double-pendulum suspension. The upper mass will be suspended on a single loop to allow the orientation of the lower mass to be controlled by tilting and rotation of the upper mass. Another pendulum will be mounted with a reaction mass close to the upper mass to allow electronic damping and orientation control of the pendulum system. For certain of the test masses a second reaction mass will be suspended below the first one to allow direct electronic feedback to the position of the test mass itself. In most cases the forces required for control of position and orientation will be imposed by coil-and-magnet systems, but electrostatic systems may be used for those forces which have to be applied directly to the test masses. Experimental studies of multiple mass systems of a similar type have been carried out in Glasgow (Veitch *et al.* 1993 [20]), and systems of a similar type have been installed in the 30 m prototype at MPQ. Automatic alignment systems based on the technique demonstrated by Morrison *et al.* (1994) [21, 22] on the 10 m prototype interferometer in Glasgow, and now being installed in the 30 m prototype at MPQ, will be implemented to maintain optimum orientation of the principal optical components.

### 4.4. Thermal noise of pendulum and internal modes

A dominant noise source in laser interferometric detectors is expected to be thermal noise associated with the pendulum modes of the suspended test masses, with the violin modes of the suspension wires, and with the internal modes of the test masses.

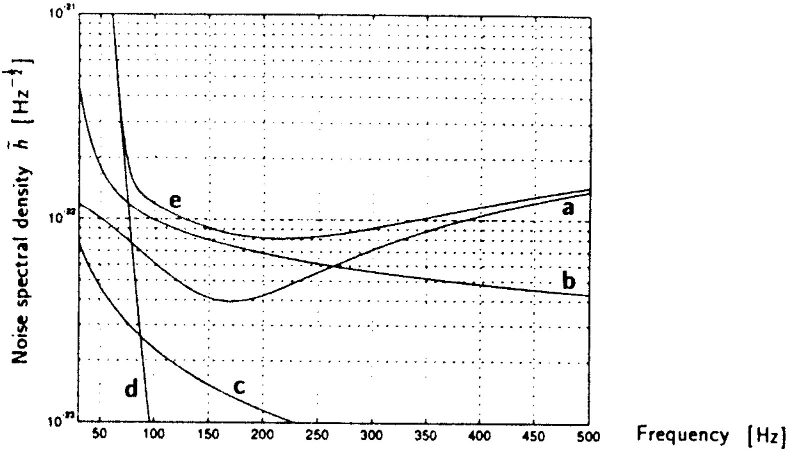

**Figure 1:** *Expected noise budget of the proposed 600 m detector. Curve* **a** *is the photoelectron shot noise for a 4 pass delay line illuminated with 5 W of laser light (1.06 μm) and typical mirror losses of 20 ppm per mirror. The system incorporates dual recycling, with a power recycling factor of 2000 and the signal recycling set to give relatively wide bandwidth. Curve* **b** *is the thermal noise in the system. The test masses are each 16 kg, of fused silica of 25 cm diameter and 15 cm thickness, as is the beamsplitter. The quality factors of the internal modes are taken to be $5 \times 10^6$ and of the pendulums to be $10^8$. Curve* **c** *represents the limit set by the Heisenberg Uncertainty Principle. Curve* **d** *represents a likely seismic noise limit for the sensitive components isolated by 4 layer stacks and suspended as double pendulums. Curve* **e** *is the overall noise spectrum of the proposed 600 m detector, obtained by the combination of limits in curves* **a** *to* **d**.

To minimise the thermal noise contributions in the bandwidth of interest, very high quality factors (Q), *i.e.* low losses, are required for the suspension wires and the test masses. It has recently been shown by Logan *et al.* (1993) [23] and independently by Gillespie and Raab (1993) [24] and by González and Saulson (1994) [25] that the Q factor of the simple pendulum mode is related to that of the suspension violin modes. Thus for very low suspension losses very high Q material must be used also for the suspension wires. It was also shown originally by Martin (1978) [26] and recently by Quinn *et al.* (1994) [27] that mechanical clamping of suspension wires or membranes leads to significant lowering of pendulum Q. Thus we intend to use a material of intrinsically high Q for the test masses and suspension wires (fused silica) and to avoid mechanical clamping wherever possible.

In our proposed interferometer the lower fused silica test masses will be suspended from upper masses, also of fused silica, on double loops of fused silica fibre. These will be welded or optically contacted to the fused silica masses in order to obtain very high Q for both the pendulum mode and the internal modes of the masses.

Test experiments by Martin (1978) [26] and more recently by Braginsky *et al.* (1993) [28] suggest that Q factors of $5 \times 10^7$ for the *pendulum mode* should be obtainable and experiments on silicon by Logan (1993) [29] and on fused silica by the VIRGO group [30] indicate that Q factors for the *internal modes* of the test masses of $5 \times 10^6$ should be achievable with such a system. It should be noted that as a result of the mechanical filtering action of the lower pendulum, thermal noise associated with the upper mass and its pendulum is not so important and thus a loop of steel wire may be used for its suspension.

### 4.5. Sensitivity to be achieved

In the interferometer system envisaged, the noise sources discussed above add up as shown in Figure 1. The noise is expressed as the *linear* spectral density of the apparent strain, $\tilde{h}(f)$. The assumptions made are given in the caption of Figure 1.

As becomes apparent, thermal noise from the suspension and the internal modes is expected to limit the sensitivity over a significant part of the frequency range (as shown in Figure 1). This is why cooling the test masses is an approach seriously to be considered. The proposed design does not preclude such a sensitivity-enhancing scheme.

## 5. Previous work in the field

Both the MPQ and Glasgow groups have carried out a large amount of development work over the last 15 years. The prototype detectors at Glasgow and MPQ Garching have achieved strain sensitivities of approximately $10^{-19}/\sqrt{\mathrm{Hz}}$ over a kilohertz bandwidth and studies of many aspects of laser systems, suspensions, autoalignment techniques, mirror quality, and mirror heating and scattering problems have been tackled. New methods of improving the sensitivity of optical interferometers have been invented both at Glasgow and MPQ, and new laser systems of high stability and power have been developed at Hannover.

For a number of years the Cardiff group have been studying the characteristics of possible sources of gravitational waves. This work led to a significant programme of investigation of algorithms for searching for signals in noise, and also to the development of a powerful software environment for wide-ranging analysis of data from detectors.

The prototype detectors at MPQ and Glasgow were run in coincidence for 100 hours in 1989 with much of the data analysis undertaken by the Cardiff group. The results are currently being published (Nicholson *et al.* 1994 [31]). A significant result of this analysis is that the presence of a low rate of spurious pulses on the detector outputs had little effect on the sensitivity of the search for gravitational waves. In a search for a reported pulsar source, Niebauer *et al.* 1993 [32] developed an efficient algorithm with which the large volume of data was greatly reduced, thus opening the way for sophisticated searches even for unknown sources.