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"Proposal for a 600 m Laser Interferometric Gravitational Wave Antenna — GEO 600," presented to PPARC, by J. Hough, G. P. Newton, N. A. Robertson, H. Ward, B. F. Schutz, K. Danzmann, A. Rüdiger, R. Schilling, W. Winkler, and colleagues, March 22, 1994

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LIGO-T940083-00-M

Proposal for a 600 m Laser Interferometric Gravitational Wave Antenna – GEO 600 –

presented to PPARC

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March 22, 1994

Abstract

In this proposal we request that PPARC consider contributing partial funding (approximately £2M plus VAT) to the high technology part of 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). The total cost is estimated to be £4M including contingency. The civil engineering work will be undertaken under the direction of Hannover, the vacuum system will be constructed by Hannover with the advice of J.R.J. Bennett of Rutherford Appleton Laboratory, the technology will be developed by Hannover, MPQ and Glasgow working in close collaboration (K. Danzmann and colleagues and J. Hough and colleagues); theoretical input on astrophysical matters and the development of data analysis techniques and algorithms will be undertaken at the University of Wales (B. Schutz and colleagues).

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 systems. 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.

Following many years of development work on prototype detectors¹, mainly in Germany, the UK and the USA, three large detector systems have been funded worldwide. Two of these - forming the LIGO project [1] - 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 [2] - 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 Australia with the long term goal of constructing a 3 km arm length detector.

The original German-British project [3] - later known as GEO - proposed and agreed in principle in the UK in 1990, was cancelled in 1991 due to lack of funding. It is our purpose in this document to propose a new advanced detector project of 600 m arm length - GEO 600.

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, 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[4], 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 a month or so, 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 SN1987A 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 3×10^{-26} at ~ 346 Hz. Similar techniques might detect a rapidly spinning neutron star rotating at the Chandrasekhar-Friedman-Schutz (CFS) instability point.

¹This development work has produced a number of technological spin-offs and has been of considerable interest to the general public (see Appendix H).

2.2 Immediate detection aims

The present proposal 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, a number of astrophysical developments since the original GEO/LIGO/VIRGO proposals were written some 5 years ago have made strong gravitational waves seem much more likely for some 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 SN1987A) 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* [5] of a 467 Hz optical pulsar in SN1987A, 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 [6] 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 [7] 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 5×10^{-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 B1913+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 [8, 9] 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 3×10^{-26} at 346 Hz. This should be detectable by GEO 600 in a year of observing. Significantly, the new pulsar in SN1987A is spinning down much more rapidly, and would radiate at $h \sim 7 \times 10^{-27}$ at 934 Hz on the same assumption; this might also be detectable. In the case of SN1987A, 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 SN1987A 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.² 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 Ω_{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- μ 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 the UK to be

²A search could, in principle, be carried out with two interferometers in one vacuum envelope in either LIGO or VIRGO but it would be very difficult to eliminate common noise sources between the interferometers.

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 is the existence of other polarisations 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.

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 600m detector would be its use as a development system for later, more sensitive detectors. It is possible that the 600m 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 (Figure B3).

3 Required detector performance

To achieve the detection aims, a sensitivity of 10^{-22} over a bandwidth of approximately 1 kHz, or a sensitivity spectral density of $3 \times 10^{-24}/\sqrt{\text{Hz}}$ from about 100 Hz is likely to be required; however the initial aims of the LIGO and VIRGO detectors is somewhat more modest than this - a few times $10^{-23}/\sqrt{\text{Hz}}$. 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 comparable 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. Expressions of support from the LIGO and VIRGO projects for our building of a 600m detector are reproduced in Appendix A. (It should be noted that one of us (JH) is the chairman of the Scientific and Technical Advisory Committee for VIRGO.)

4 Proposal to build a joint German/British 600 m baseline 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 would be built on farmland owned by the University of Hannover and available immediately for this purpose (see Appendix C). The detector would be built just below ground.

4.1 Vacuum system

The vacuum system designed by J.R.J. Bennett from RAL (Appendix D) would consist of a cluster of up to 9 stainless steel vacuum tanks each of 1m diameter at the centre of the system and one tank of the same diameter at each end of the perpendicular arms (Figure D1). The end tanks would be joined to the cluster at the middle by stainless steel vacuum pipes of 0.6m diameter. The system would be pumped by a combination of turbo molecular pumps and NEG pumps. The design would allow a vacuum pressure close to 10^{-8} mbar for H_2 and 10^{-9} mbar for other heavier gases to be achieved, 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 would be installed as shown schematically in Figure B4, this being a somewhat simplified version of the original delay line interferometer [3] proposed for the 3 km GEO detector. Power recycling would 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 [10]). Signal recycling as proposed by Meers (1988) [11] and demonstrated experimentally by Strain and Meers (1991) [12] would 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 would 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 [13]). The excess noise due to relaxation oscillations in such lasers and

its relevance for gravitational wave detectors has been studied at Glasgow by Campbell *et al* (1992) [14] and the necessary reduction in such noise by electronic feedback has been demonstrated by Rowan *et al* (1994) [15] and by Harb *et al* [16]. The laser would 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) [17]. The interferometer would be locked on a null fringe using techniques partly outlined in the original German/British proposal [3] and taken further in an experimental demonstration on a table top by Strain [12]. 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[18].

The beamsplitter, and the test masses that form the main mirrors of the interferometer, would consist of solid cylinders of fused silica, approximately 25 cm diameter and 15 cm thickness, with supersmooth and dielectrically coated surfaces. The recycling mirrors would be similar. The coatings would 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 would 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 would therefore be encapsulated in very soft metal bellows which would be pumped separately from the rest of the system. Each test mass, the beamsplitter, and each recycling mirror would be suspended on a double loop as the lower mass of a double-pendulum suspension. The upper mass would 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 would 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 would be suspended below the first one to allow direct electronic feedback to the position of the test mass itself (see Figure B6). In most cases the forces required for control of position and orientation would 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 [19]), 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) [20, 21] on the 10 m prototype interferometer in Glasgow, and now being installed in the 30 m prototype at MPQ, would be implemented to maintain optimum orientation of the principal optical components.

4.4 Thermal noise associated with the pendulum and internal modes of the test masses

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. 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) [22] and independently by Gillespie and Raab (1993) [23] and by González and Saulson (1994) [24] 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) [25] and recently by Quinn *et al* (1994) [26] 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 would be suspended from upper masses, also of fused silica, on double loops of fused silica fibre. These would 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 in Glasgow by Martin (1978) [25] and more recently by Braginsky *et al* (1993) [27] suggest that Q factors of 5×10^7 for the *pendulum mode* should be obtainable and experiments on silicon by Logan in Glasgow (1993) [28] and on fused silica by the VIRGO group [29] indicate that Q factors for the *internal modes* of the test masses of 5×10^6 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. Nevertheless, 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 Figures B1-3). 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. The possible gain in sensitivity is indicated in Figure B3.

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 as may be seen from the relatively recent publications listed in Appendix E. The prototype detectors at Glasgow and MPQ Garching have achieved strain sensitivities of approximately $10^{-19}/\sqrt{\text{Hz}}$ 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 [30]). 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 [31] 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.

6 Funding and timescales

As is outlined in Appendix F the total building cost for the detector (excluding scientific and technical manpower) is currently estimated as approximately 10.3 MDM, of which 2.6 MDM is available from sources in Hannover during 1994-6 and 1.6 MDM is available from the Max-Planck-Gesellschaft from 1994-8. This funding will be used for site preparation, civil engineering, and purchase and building of the vacuum system with some contribution to suspensions and optical components. Of the remaining 6.1 MDM, 1 MDM will be requested from BMFT. The remaining 5.1 MDM, for part of the suspension work and most of the advanced optics required, is the subject of this proposal to PPARC and would be required starting in 1996.

We believe that the vacuum shell would be available for initial installation of suspension systems and optics by 1996 and that the detector would be operational during 1998.

7 Management of the project

Although situated in Hannover, the detector would be built under the control of the Max-Planck-Institut für Quantenoptik, Garching, which is currently setting up a remote branch in Hannover.

A project management committee with representation from MPQ, University of Hannover, University of Glasgow, University of Wales and PPARC would be established to advise the participating institutions on the progress of the project both financially and scientifically. The Universities of Glasgow and Wales will be responsible for the management of all resources awarded as PPARC grants.

A scientific/technical committee under the direction of Prof. K. Danzmann (Hannover and MPQ) and Prof. J. Hough (Glasgow) and consisting of the principal scientists involved in the project will be responsible for the planning and progressing of the project and will be directly responsible to the management committee.

Further details of the structure and responsibilities will be discussed at a later stage.

8 Personnel associated with the project

The people associated are listed in Appendix G.

9 Resource implications for Glasgow and Cardiff

The Glasgow group currently consists of 4 academic staff, one SERC Research Fellow, 3 postdoctoral workers, 4 research students and 4 technicians and currently is funded by SERC at a rate of approximately £300k per annum. It is envisaged that an increase to 5 postdoctoral workers would be required and that costs for consumables would double from its present level of approximately £45k per annum. Travel also would increase from its present level of about £4k per annum to about £12k per annum in 1995 and then reaching a steady level of approximately £20k per annum for the installation, commissioning and operating phases.

In Cardiff, the present complement of 2 pdras and one programmer for gravitational wave work is fully committed to ongoing projects, including the collaborations with LIGO and VIRGO on software and analysis methods. For GEO 600 Cardiff would take responsibility for the design of the data acquisition network, the data archive, the quick-look analysis system, the interface between the analysis and control systems, and the data communications with the outside world. Because these responsibilities can be shared to some extent with present pdras, we would require one additional pdra to work full-time on GEO600, including spending considerable time in Hannover during the installation period. Travel costs would have to be increased by about £10k per annum.

We would require data archiving and analysis equipment in Cardiff as well as at the experiment in Hannover. The analysis computer would have to be capable of speeds of at least 100 Mflops, which is most easily attained today with a small parallel computer costing perhaps £30k, interfaced to a host workstation costing £10k. Including archiving equipment, database software, and fast (optical) data interfaces, the extra equipment might total £60k. There would be consumable costs (magnetic tapes for archiving not only GEO 600 data but also that of the other detectors) of perhaps £10k per year.

10 Future prospects

It is a particular feature of the proposed antenna that it lends itself to future modifications and enhancements. As mentioned earlier cooling of the test masses to approximately 20 K could be carried out with some added technical difficulty and extra cost and could allow considerably enhanced narrowband sensitivity for continuous sources such as pulsars (Figure B3). Furthermore, the optical systems developed would be excellent candidates for use in the next stages of LIGO and VIRGO.

11 Conclusion

The funding of this project will give the research groups in Glasgow and Cardiff a realistic opportunity to be a part of the initial coincidence experiments to search for gravitational waves at an exciting level of sensitivity and at a fraction of the cost of the original GEO experiment. It will also considerably enhance the prospects for contribution to higher sensitivity experiments in the future.

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A Letters of support

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February 18, 1994

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Appelstraße 2
D-3000 Hannover 1, Germany

Dear Jim and Karsten,

It was good to have a chance to talk with Jim at the workshop on thermal noise in laser interferometer gravitational wave detectors. I was especially excited to hear about the plans you are formulating for building a 600 m interferometer ("GEO 600").

I would like to encourage you in the development of the GEO 600 interferometer. This proposed instrument should become one of the premier research instruments for the development of laser interferometer gravitational wave detectors. The technical directions that you outlined for GEO 600 research are certainly of high interest for LIGO and we would wish to establish a meaningful collaboration based on these. In particular, the optical schemes that you are planning to test there are definite candidates for inclusion in future LIGO interferometers.

When you succeed in getting your interferometer operating, we would also be interested in exploring opportunities for observing in coincidence. Although it is likely that the two instruments will have different sensitivities as a function of frequency, such coincidence runs would have great value to all concerned. The LIGO project is firmly committed to the international effort to study gravitational waves and would welcome any meaningful opportunities for collaborative experiments.

We are, of course, willing to share any data or other information that we have which would be useful for your design. The technical interchanges we have had with your groups over the years have always been both enjoyable and fruitful. If there is anything that we can do to aid your development, please let us know.

Sincerely,


Stanley E. Whitcomb
Deputy Director

SEW/bb

14

cc: B. Barish
K. Thorne



Istituto Nazionale di Fisica Nucleare

Sezione di Pisa

November 2, 1993

Pisa, It.

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Dr. Hough
University of Glasgow
Dept. of Physics
GLASGOW G 128QQ - GB

Dear Jim,

we are also very pleased that we can finally start a real collaboration. Harry's trip to Orsay is very stimulating and useful to us, and we hope that the realizations which will result from his interaction with our physicists and engineers will also benefit you.

We are also pleased that you seem to have found a way of starting the construction of a "long prototype". Such a system will certainly be very useful for the experimentation on advanced detectors. We are obviously very interested by this program, and we hope we will collaborate on this instrument too.

We wish to propose to help you as much as we can: in the nearest future, if your planning and costing work may benefit from our recent work, we will be happy to communicate all the information you want.

Adalberto Giazotto

Alain Brillet

B Optical layout

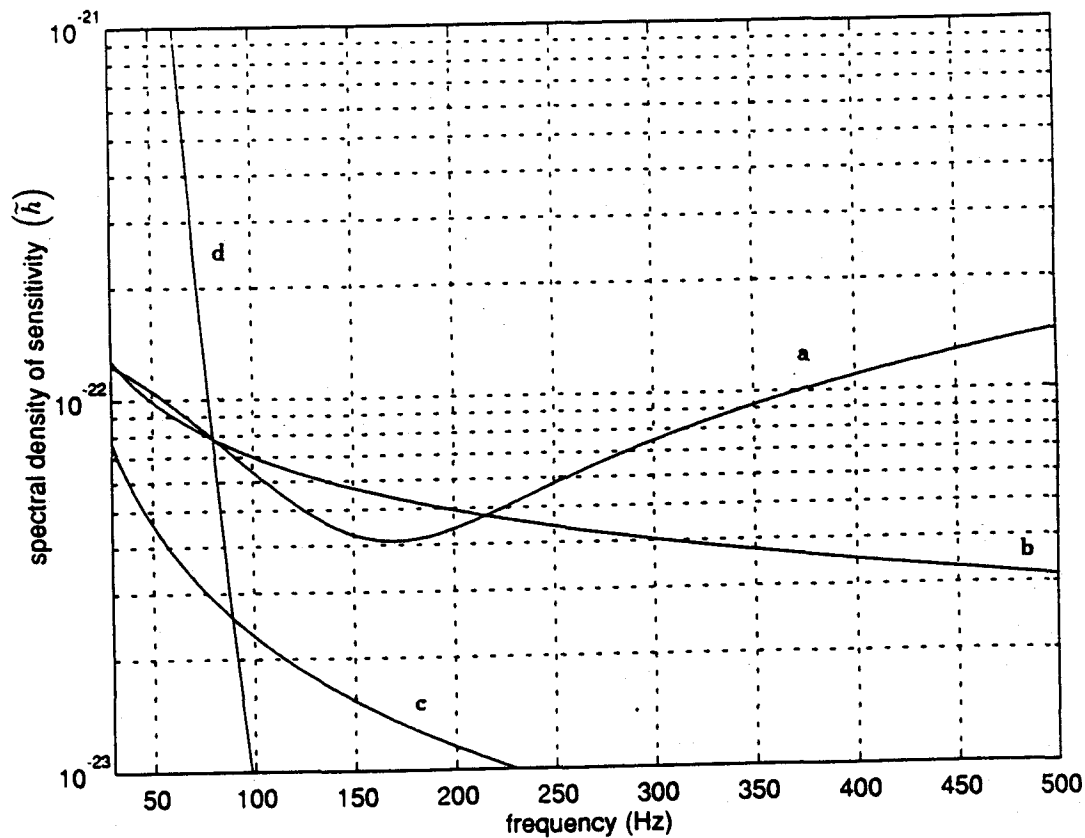


Figure B1: Possible sensitivity limits to the proposed 600 m detector. Curve a is the photoelectron shot noise for a 4 pass delay line illuminated with 5 W of laser light ($1.06 \mu\text{m}$) and typical mirror losses of 20 ppm per mirror. The system incorporates dual recycling, with a power recycling 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 5×10^6 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.

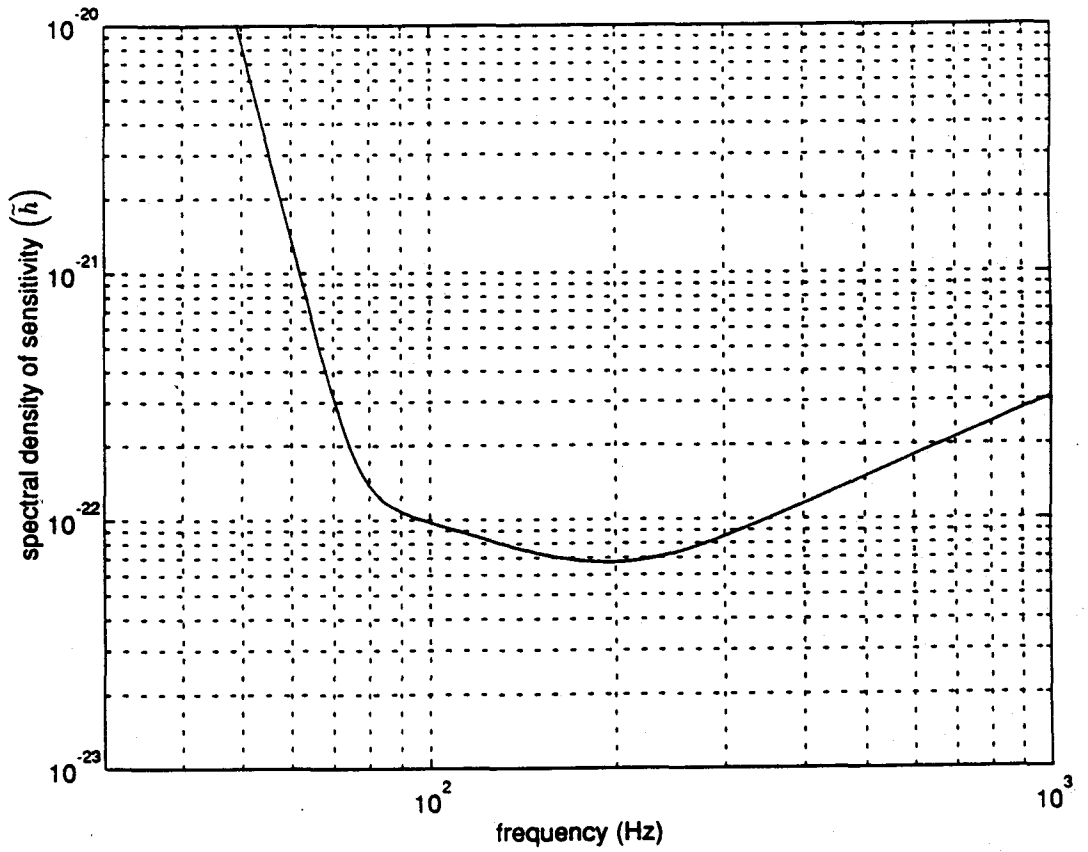


Figure B2: Overall sensitivity limit to the proposed 600m detector, obtained by the combination of limits shown in Figure B1.

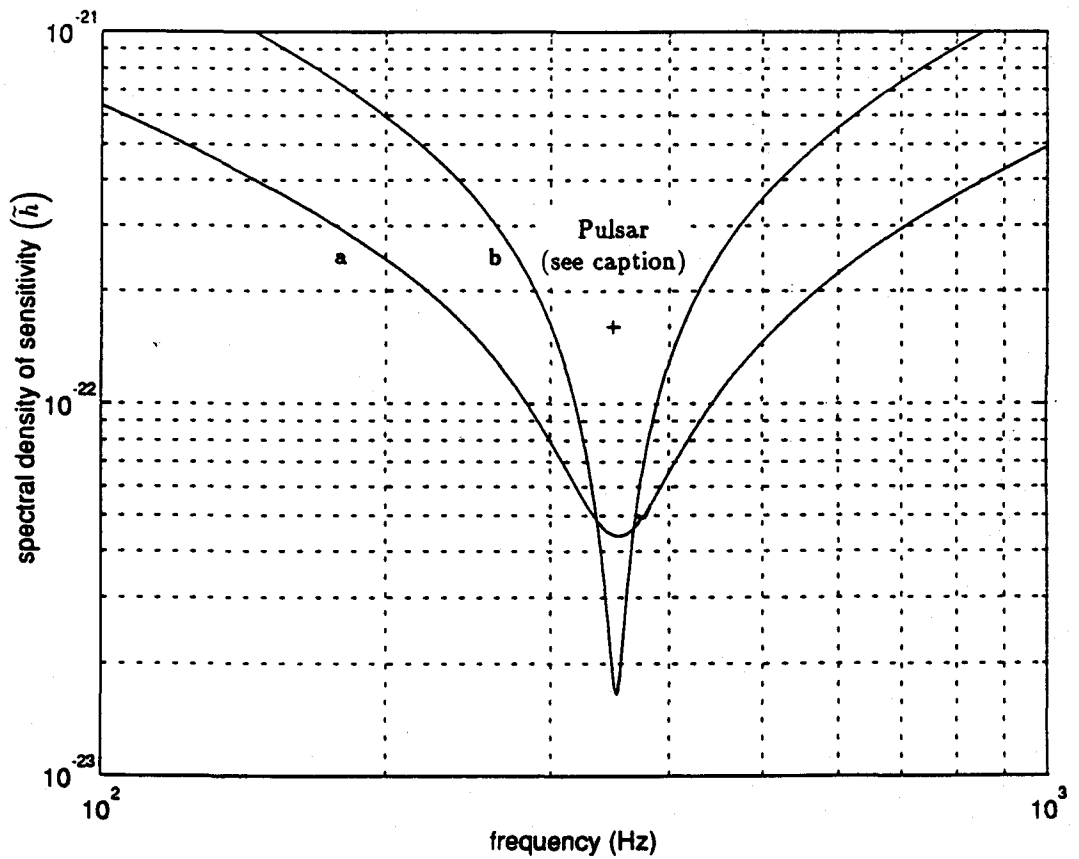


Figure B3: Possible sensitivity limit to the proposed 600 m detector when the signal recycling is optimised for narrowband operation at 346 Hz. In case a the test masses are at room temperature. In case b the masses are cooled to 20 K and the bandwidth further narrowed. An upper limit to the effective signal from pulsar PSR J0437-4715, observed for 3×10^7 s, is shown.

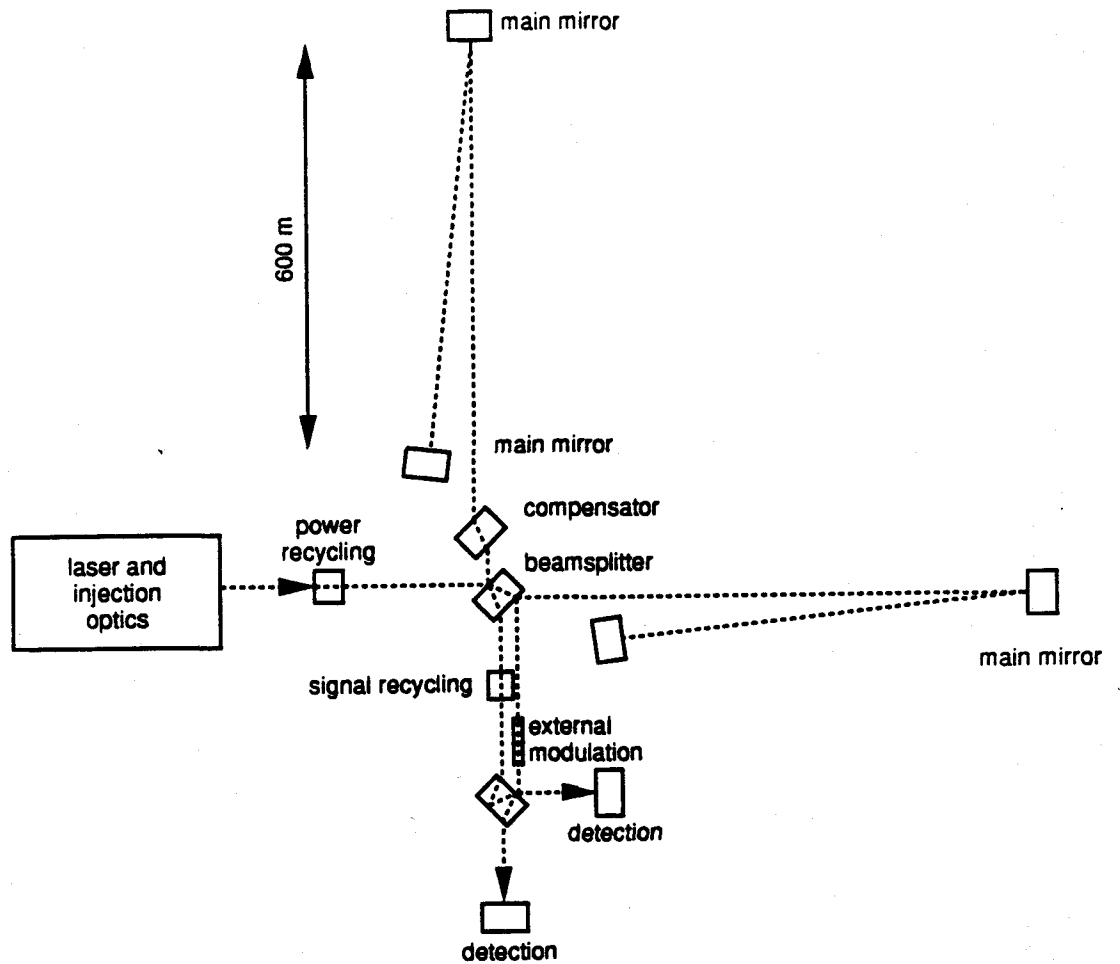
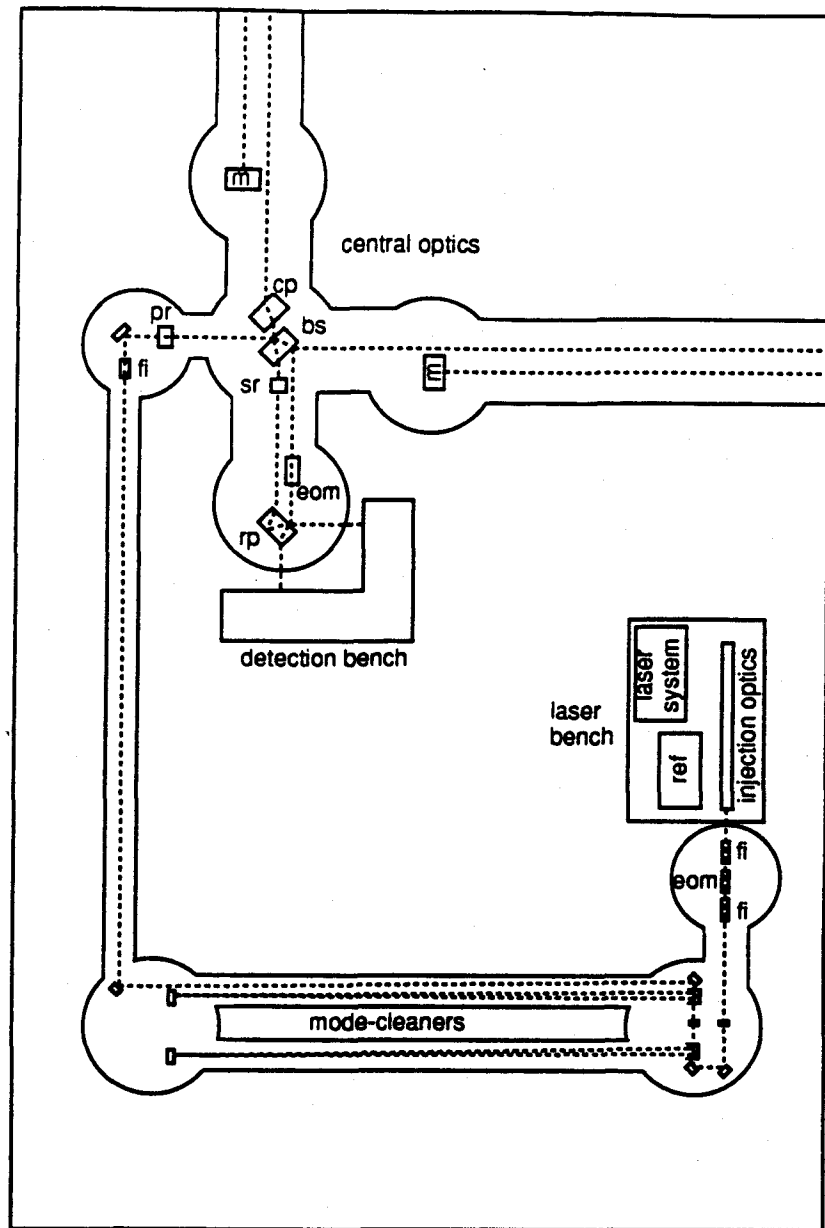
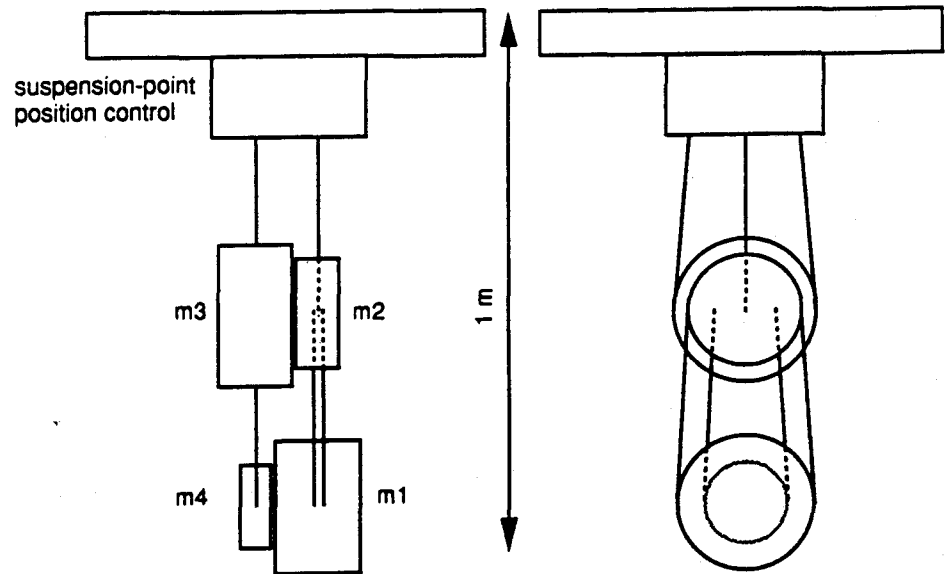


Figure B4: Schematic diagram of a 4 pass delay line interferometer with both power and signal recycling (i.e. dual recycling). The angles and lengths are not to scale. The test masses for the interferometer are formed by the main mirrors and the beamsplitter.



- Key**
- m main mirror
 - pr power-recycling mirror
 - sr signal-recycling mirror
 - bs beamsplitter
 - cp compensation plate
 - rp recombination plate
 - eom electro-optic modulator
 - ref reference cavity for frequency stabilisation
 - fi faraday isolator

Figure B5: Possible scale layout of the optics in the centre station of the 600 m interferometer.



- m1 test mass (fused-silica)
- m2 intermediate mass (fused-silica)
- m3 reaction mass for intermediate mass
- m4 reaction mass for test mass (if required)

This diagram is approximately to scale.

Figure B6: Schematic diagram of a possible double pendulum suspension for a test mass (main mirror).

C Interferometer site

The site selection and preparation procedure, including survey, environmental studies, and obtaining planning and various other permits has been the most time consuming part of all large detector projects. Fortunately, GEO 600 does not suffer from these constraints, and building could commence immediately. We do thus have the chance to create a really quick and flexible project.

The instrument will be built on land owned by the state government of Niedersachsen and administered under the jurisdiction of the University of Hannover. The specific site in question is situated in the small town of Ruthe near Sarstedt, just 12 km south of the center of Hannover and 25 km from the Hannover international airport. The site is being used as experimental farmland by the Department for Agriculture of the University of Hannover.

During the seismological survey for the GEO detector, this part of Germany turned out to show a microseismic activity which is low enough for a gravitational wave detector. No major man-made noise sources are in the vicinity, the nearest being a railway line at a distance of 2 km. After decades of agricultural use, the water table at the site is known to be low enough to be of no problem.

The detector will be built along existing, and only occasionally used, farm roads, not inhibiting usage of the farmland. The vacuum tube will be just below ground, constructed in an open trench about 1.5 m deep, then protected by prefabricated arches, and covered by soil. This is similar to the way the Garching 30 m prototype is constructed. The buildings at the ends of the arms and at the vertex of the L-shaped detector have a size of about 15 m² and 60 m², respectively. They will be constructed from widely used and inexpensive prefabricated structures.

Legally, the detector will be built and operated by the Max-Planck-Society, but the responsibility for the construction will be delegated to the Staatshochbauamt I, which is pursuing all construction projects on University grounds. The Staatshochbauamt I is also the authority responsible for the approvals process. A contract between the University of Hannover and the Max-Planck-Society is ready for signature. A building permit has been obtained.

Bild 4:
Grundstücksverfügbarkeit (Stand 1965)
Standort Ruthe / Sarstedt

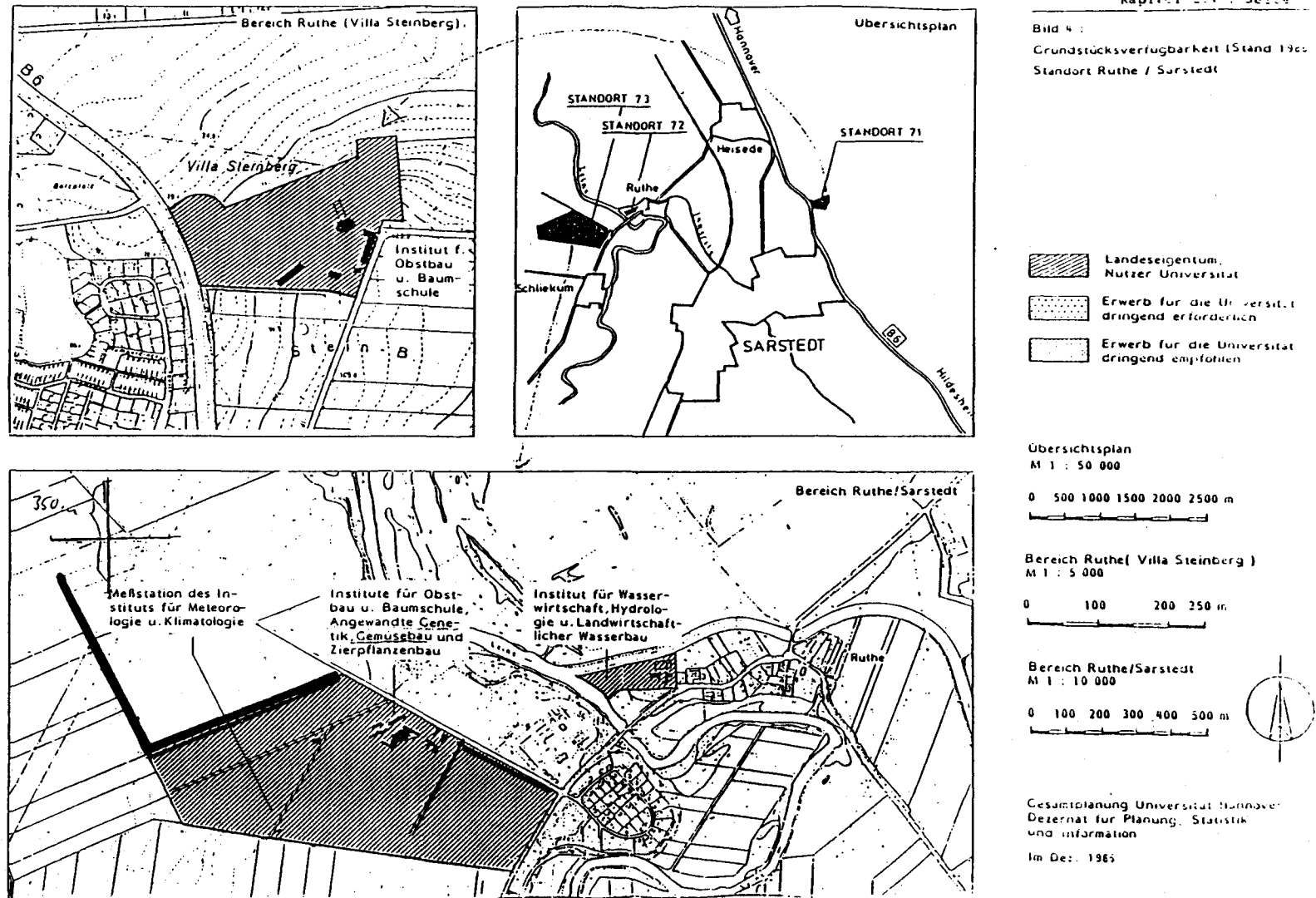


Figure C1: A map of the site for GEO 600. The position of the proposed detector is shown by bold black lines.

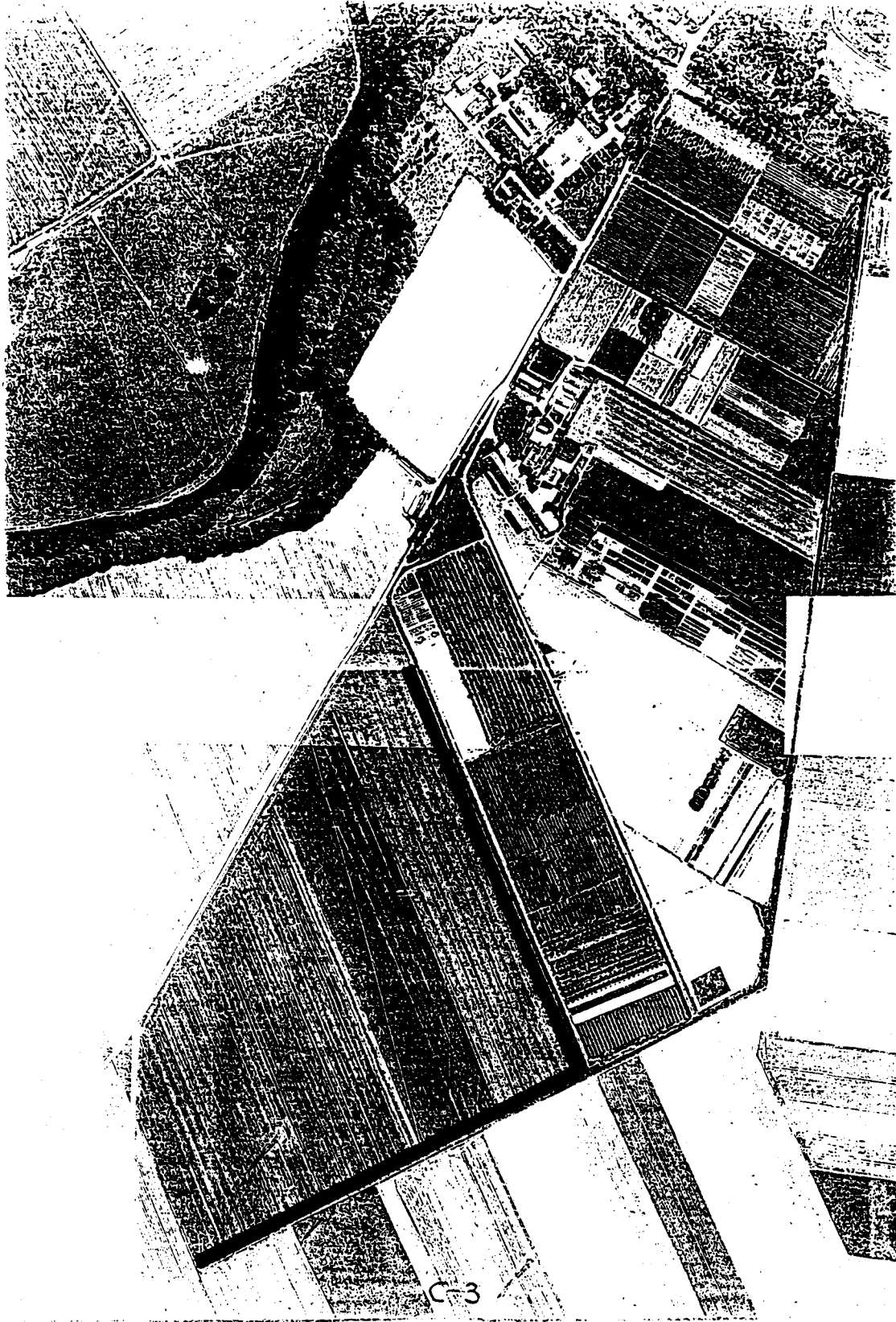


Figure C2: An aerial photograph of the site for GEO 600. The position of the proposed detector is shown by bold black lines.

D Vacuum system for the interferometer

D.1 Vacuum requirements

Various considerations make ultra high vacuum (UHV) mandatory for the GEO 600 project. Some of them are concerned with noise introduced to the measurement, another one with possible contamination of the very high quality mirrors.

Refractive index fluctuations

Statistical fluctuations in the residual gas (in thermodynamical equilibrium) give rise to a strain noise density $\tilde{h}(f)$ that turns out to be a white noise in the frequency range of interest, and which is given by [3]

$$\tilde{h}^2 \approx \frac{2\sqrt{2}(n_0 - 1)^2}{N_0 v_0} \left(\frac{p}{p_0}\right) \frac{1}{\ell \bar{w}},$$

with N_0 being Avogadro's constant (2.69×10^{25} molecules/m³), n_0 and v_0 the refractive index and speed of sound at standard pressure p_0 . The dependence on the beam geometry (on the arm length ℓ and the beam's half-width \bar{w}) was derived assuming a light beam of constant (or not too strongly varying) width $2\bar{w}$.

The optical design of GEO 600 is likely to have an appreciable variation in beam width from the waist (w_0) in the central tank to the end mirrors, $w(\ell)$, at distance ℓ ($= 600$ m). This allows smaller optical components (beam splitter, Pockels cells, isolators, etc.) to be used in the central tank. But too large a beam diameter $2w(\ell)$ would require end mirrors that become unwieldy. Therefore a ratio $w(\ell)/w_0 > 10$ is unlikely.

Throughout this range of reasonable choices for w , w_0 we can approximate the refractive-index noise by [32]

$$\tilde{h}^2 \approx \frac{2\sqrt{2}(n_0 - 1)^2}{N_0 v_0} \left(\frac{p}{p_0}\right) \sqrt{\frac{\pi}{\ell^3 \lambda}}.$$

To meet the GEO 600 specifications of $\tilde{h} = 5 \times 10^{-24} / \sqrt{\text{Hz}}$, with $\ell = 600$ m, $\lambda = 1 \mu\text{m}$. for hydrogen ($v_0 = 1580$ m/s, $n_0 - 1 = 1.4 \times 10^{-4}$) we should not exceed a residual gas pressure of

$$p_{\text{H}_2} = 1.6 \times 10^{-7} \text{ mbar},$$

and for heavier gases (say, N_2 , with $v_0 \approx 500$ m/s and $n_0 - 1 \approx 3 \times 10^{-4}$) a pressure of

$$p_{\text{N}_2} = 1.1 \times 10^{-8} \text{ mbar}.$$

Typically, hydrogen is by far the most abundant residual gas in UHV systems, but its low value of $(n_0 - 1)$ and its high velocity v_0 make it much less critical than other gases. Fortunately, on the other hand, the turbo-molecular pumps to be used in the GEO 600 vacuum system are particularly efficient in pumping the heavier gases (N_2 , H_2O , hydrocarbons) where the requirements are more stringent. Therefore, a much lower target pressure p_{hg} for the total of all heavier gases seems to be quite compatible with the H_2 target. For the noise to be sufficiently below the GEO 600 specifications, the following very conservative target values were chosen as vacuum requirements:

$$\hat{p}_{\text{H}_2} < 10^{-8} \text{ mbar},$$

$$\hat{p}_{hg} < 10^{-9} \text{ mbar.}$$

Momentum transfer

Exchange of momentum between the test mass (main mirror) and the surrounding gas can affect measurement in two ways.

One is the deterioration of the mechanical quality factors Q of pendulum and vibrational modes of the test mass. The other one is an acoustical coupling to the motions of the vacuum tank walls.

Into both these effects, a frequency (ω) dependent factor

$$\delta = \frac{p}{v_0 D \rho \omega}$$

enters, with D and ρ the thickness and density of the test mass. This factor has the meaning of an attenuation $\delta \approx 1/Q$ in the first effect; and in the second effect the meaning of a transfer function $\delta \approx \bar{x}_m/\bar{x}_w$ between the motion \bar{x}_w of the tank walls and the resulting motion of the test mass, \bar{x}_m . At the given target pressure $p_{H_2} = 10^{-8}$ mbar, both effects become negligible.

Mirror contamination

The very high quality of the main mirrors can be maintained only if deposition of contaminants is kept extremely low. Of particular danger are hydrocarbons, which might be cracked and "burnt in" by the extremely high light intensities envisaged.

No numerical data can be given (a recent paper by Abramovici *et al* [33] can be used to set safe limits), but extreme care is called for. This is why the "rubber" springs in the seismic isolation stacks are to be encapsulated in stainless steel bellows.

D.2 Vacuum system

The basic vacuum system consists of two tubes, each 600 m long arranged in the form of an L. The bore of the tube must be at least 60cm diameter to accommodate the laser beams and baffles with the necessary clearance. The experiment tank stations, containing the test masses, optics and other equipment, are located at the ends of the arms. These tanks are 0.8m diameter and 1.5m high except for the main centre tank which is 1.2m diameter.

To keep the noise from the random fluctuations in the vacuum pressure below other noise limits requires the average pressure in the optical path of the interferometer to be $< 10^{-8}$ mbar for hydrogen and $< 10^{-9}$ mbar for the sum of all other gases.

It is assumed that all the materials in the vacuum system are metal and ceramic with no hydrocarbons except for the main seals in the valves at the ends of the arms of the detector. All demountable joints have metal gaskets. All the main components are made of 316L stainless steel. the tube is constructed from 0.5mm thick stainless steel sheet, convoluted to give stability against collapse from the external atmospheric pressure[34]. Smooth, nonconvoluted, tube would need to be 7 mm thick for the same stability. Smooth tube is more expensive than corrugated tube, and in addition the rigid tube requires more massive supports and adjustments to provide alignment and costly flexible bellows to take

up misalignments and thermal expansion. After processing and baking to 200°C under vacuum the tube has a specific outgassing rate[35] of $< 10^{-12}$ mbar/l/s/cm². It is unlikely that the equipment in the tanks can withstand a bake above 80°C and therefore it is assumed that their outgassing rate will be 10^{-11} mbar/l/s/cm².

The vacuum pumping has been calculated on the basis of the outgassing rates given above and the volume (170m³ and ~ 1 m³ for each tube and tank, respectively) and surface area (1.8×10^7 cm² and 10^6 cm² for each tube and tank including its equipment, respectively) of the components. The time for pumping down to the required pressure is taken as 1-2 weeks for the tubes and 1-2 days for the tanks.

Figure D1 shows the pumping system. A single Roots/rotary pump combination rough out either of the 2 arms of centre station tanks. The 2000 l/s turbomolecular pump then brings the pressure down to the required value. Turbomolecular pumps with slightly larger than usual rotary pumps, serve to rough and pump down the stations at the far ends of the arms. The turbomolecular pumps will be of high compression ratio design, incorporating drag pumps to allow the use of oil-free diaphragm backing pumps. The 1000 l/s NEG pumps in the arms can be brought into operation when the system is clean and well tested and will maintain the vacuum when the arms are isolated from the end stations. If mechanical vibration of the turbomolecular pumps from the backing pumps proves troublesome, then NEG pumps can be added to the tanks at little extra cost (\sim £14k). In this case a small (50 l/s), well isolated, magnetically levitated turbomolecular pump would be needed to pump those gases (noble gases and hydrocarbons) not removed by the NEG's.

Measurement of the vacuum pressure will be by Penning and wide range Pirani gauges, with simple quadruple mass spectrometers to evaluate the state of the vacuum and to help leak detection. All controls will be local and manual, but incorporate automatic fail safe operations in the event of failures. The status will be read through the facility control computer system.

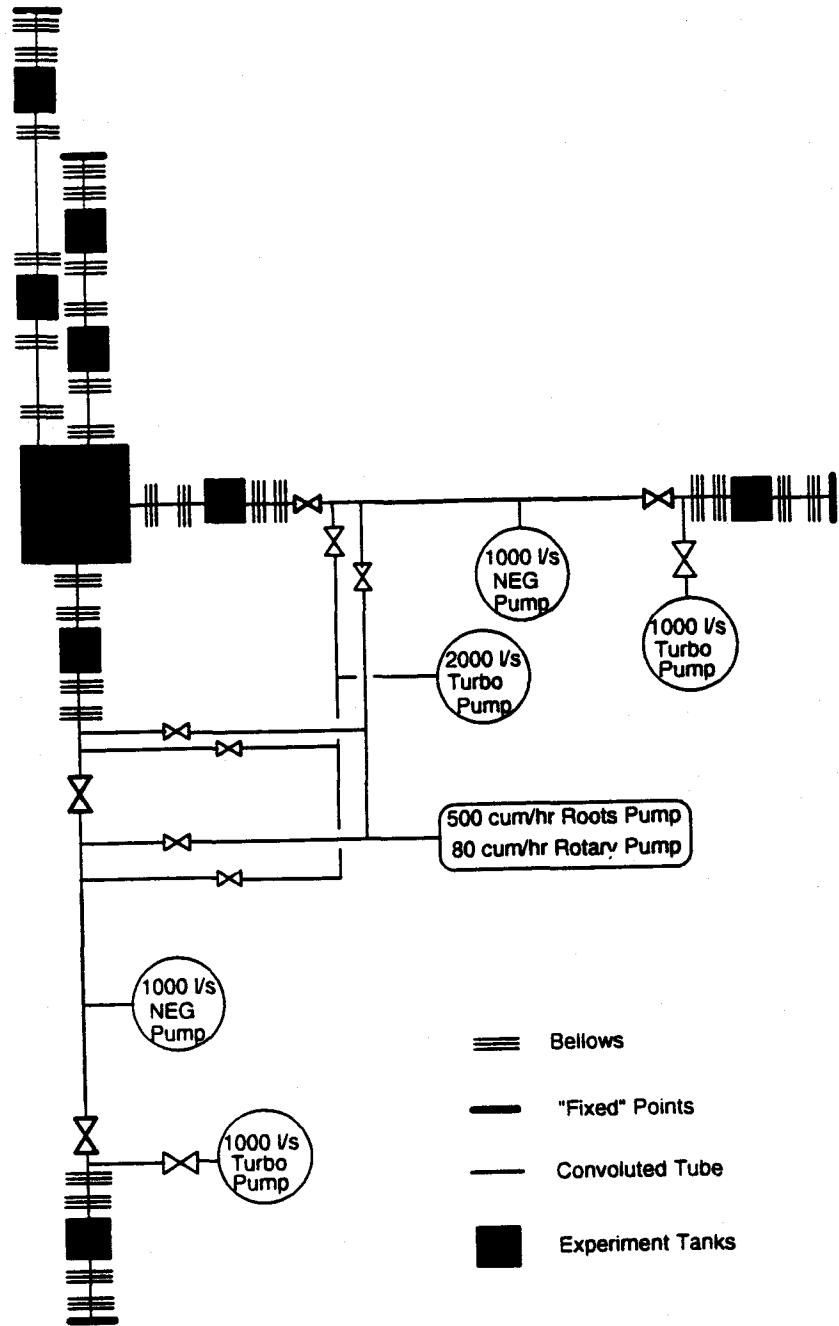


Figure D1: Schematic diagram of the vacuum system.

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F Cost

Summary of costs for GEO 600

	MDM (1994)
Civil engineering	1
Vacuum	3.1
+ Manpower	0.45
Optics	2
Suspension etc	0.4
Control	0.8
Data acquisition	0.65
Laser	1
10% Contingency	0.94
Total	10.34
Hannover/MPG contribution	4.24
Proposed BMFT contribution	1
Proposed UK capital contribution	5.1
Total UK contribution	5.1 + VAT + Glasgow/Cardiff running costs

Breakdown of costs

Optics	number	kDM
Main mirrors	4	500
Beamsplitter	1	175
Compensator	1	175
2nd Beamsplitter	1	50
Faraday isolators	5	250
Mode cleaners	3	225
Recycling mirrors	4	100
Electro-optic modulators	8	100
General mirrors, lenses etc		125
Laser bench, ref. cavity etc		175
Spares		125
Total		2000
Servo and Control Systems		
Laser servo systems	6	83
Alignment systems	13	55
Crude alignment		50
Instrumentation		368
Assembly		200
Spares		44
Total		800
Seismic isolation and suspensions		
Double pendulums	14	15
Lead bricks (+ top plates)	75	20
Springs (bellows)	300	60
Coils	300	60
Viewports	20	25
Stepper motors	70	70
Movable stages	70	35
Local control units	50	30
Racks, power supplies		20
Stepper control	5	5
Computers	4	30
A/D converters, cables etc		20
Spares		10
Total		400
Data acquisition/analysis		
Network		32
Local 'first look'		75
Data storage		300
Media costs (2 years at 1.7 GB/day)		243
Total		650

G Personnel associated with the GEO project

Glasgow	Staff	J. Hough (Professor), N.A. Robertson (Senior Lecturer), G.P. Newton (Lecturer), H. Ward (Lecturer)
	Research Fellow	J.E. Logan (currently in Garching)
	Research Assistants	A.M. Campbell, D.I. Robertson, K. Strain
	Research Students	S. Killbourn, A. McLaren, S. Rowan, K. Skeldon
	Technicians	C. Craig, D. Edwards, A. Latta, A. McKellar
Hannover	Staff	K. Danzmann (Professor), P. Aufmuth, R. Rinkleff, B. Willke, H. Welling (Professor)
	Research Students	O. Jennrich, G. Müller, A. Wicht
	Diploma Students	R. Bähnisch, O. Lahayne, S. Traeger
	Laser Zentrum	A. Tünnermann, I. Freitag, D. Golla, S. Knoke, H. Schmidt, W. Schöne, H. Welling
	Technicians	H. zur Mühlen, K. Tetzlaff, H. Claus (+ mechanical workshop)
MPQ	Staff	K. Danzmann, A. Rüdiger, R. Schilling, W. Winkler H. Lück, M. Schrempel
	Engineers	A. Bachmeier, H. Klein
	Technicians	H. Emme, H. Lindner
Cardiff	Staff	B.F. Schutz (Professor)
	Research Assistants	D. Nicholson, J. Shuttleworth
	Programmer	T. Barnett
	Research Students	K. Compton, A. Wickramasinghe

H Wealth creation and public understanding

H.1 Wealth creation: technological and intellectual

The greatest additions to the wealth of information and technology available to society are created by projects which are multidisciplinary and lead to synergy effects and coherent multiplication of efforts from different forefront disciplines. GEO 600 fits this description ideally. GEO 600 is a project that challenges state-of-the-art knowledge and expertise over a broad spectrum ranging from the most abstract fundamental theory to the most applied technology and measurement science; and there are technological spin-offs to be obtained from such research, as are exemplified below.

- The technique of reflection locking a laser to a reference cavity was developed for gravitational wave detectors and now has widespread applications in frequency standards, atomic spectroscopy *etc.*
- The initial studies for the GEO project have already led to the development of a marketable industrial product used for precision wave-front characterization in the optical industry.
- An inexpensive and reliable technique to achieve low outgassing rates in ultra-high vacuum systems has been devised for the GEO project and is now being used in other experiments.
- The most perfect spherical mirror ever produced has just been finished as a prototype mirror for GEO. The technology to do this will be applied elsewhere.
- The manufacture of almost lossless optical coatings has largely been motivated in recent years by the requirements for gravitational wave detectors. The quality of these coatings, originally developed for laser gyros, has improved by nearly two orders of magnitude over the last 5 years.
- The demands of the gravity wave projects (LIGO, VIRGO, GEO) have driven and will continue to drive the development of all-solid-state cw diode-pumped laser systems with unprecedented output power and amplitude and frequency stability; applications of these range from intersatellite communications to laser television.
- The phase-gradient wave-front angle sensing techniques being developed for GEO will be usable for the automatic self-alignment of a wide range of optical systems; and the interferometer technology of GEO 600 itself, even when downgraded by orders of magnitude for practical applications, will greatly improve the state-of-the-art in interferometric sensing.
- The vibration isolation and electronic mechanical resonance suppression developed for GEO 600 will provide simple yet superior solutions for industrial applications.
- Studies of the internal dissipation in the test masses are leading to a new understanding of thermal noise in mechanical systems. Such noise sets a fundamental limitation to the performance of, for example, miniature sensors for bore-hole surveying in the oil industry.

- The data analysis demands motivate the development of inexpensive but massively parallel computer systems and algorithms to be used on them.

H.2 Public Awareness of Science

The theory of gravity is one of the most fundamental, yet least understood, of all physical theories. Observations and experimental advances are constantly triggering new theoretical work in this field. After all, it was the (unjustified) claim of experimental detection of gravity waves in the 1960s that spurred a vigorous theoretical debate about the reality of gravitational waves, following 50 years of quiescence after the initial prediction by Albert Einstein.

The award of the 1993 Nobel Prize in physics for the discovery of the binary pulsar and its use to provide indirect proof of the existence of gravitational waves has highlighted the gravitational wave field and has stimulated the interest of many people, scientists and amateurs alike. It helps to emphasise the fact that gravitational waves have not been detected directly and that such detection remains as one of the most challenging, but potentially fruitful, problems of experimental astrophysics.

Although gravitation and gravitational waves are among the least understood scientific disciplines, they appeal to the imagination of people of a wide range of experience and background. Gravity does not suffer from the same public understanding problem that other fundamental fields have. On the contrary, almost everybody has an immediate intuitive understanding of gravitation as it pervades our lives permanently and in everyday experience. This results in many demands for talks in this field to be given to astronomical societies, physical societies and to the general public. There also are requests every year for short contributions to radio programmes on science. The concept of a curved space can easily be made plausible even to lay audiences by the use of suitable demonstrations. Gravitational waves and the technology to measure them are easily imagined and appear to be an area of fascination to the population at large. Describing research in this area provides an opportunity to captivate the public imagination and contribute to the general scientific education and to the widespread acceptance of science.