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Fundamental research for the development of gravitational wave detectors in Germany

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1 Early History
When reading articles about gravitational wave detection by the American LIGO detectors, one gets the impression that this is a purely American venture. But this is not the case. The present article outlines our contribution in Germany and from the later GEO600 cooperation. The German group was formed in 1971 at the Max Planck Institute for Astrophysics (MPA) in Munich. In the late seventies, the MPA moved to Garching near Munich, together with Heinz Billing and his group and a 3 m interferometer to be used as a prototype. In the early eighties, a 30 m prototype was built at the MPA and operated there until the end of the century. In 1985, in a groundbreaking experiment, the 30 m interferometer reached the shot noise limit of the measurement—according to photo-current statistics. Therefore, in 1987, the construction of a 3 km interferometer in Germany was proposed [1]. Unfortunately, it was not funded. The American proposal for LIGO, put forward around that time as well, quoted the results obtained in Garching, showing the feasibility of such an experiment. LIGO was funded and eventually received the Nobel Prize in 2017.

In the mid-1980s, a close cooperation began between the Garching group and the group around James Hough at the University of Glasgow. In 1989, a proposal for a common German-British interferometer was put forward, which was also not funded. In 1990, Karsten Danzmann, now a professor at the University in Hannover and director of MPI for Gravitational Physics in Hannover, became the leader of the Garching group. He started the GEO600 cooperation, mainly between the Max Planck Society and the University of Glasgow, which eventually built the GEO600 gravitational wave (GW) detector in Hannover—an interferometer with a 600 m arm length. This detector has been used to observe gravitational waves and to develop and test new technologies, which have been implemented afterwards in the other interferometric GW detectors such as LIGO in America, VIRGO in Italy, or KAGRA in Japan.
In addition, pioneering work for the space mission LISA [2] and its predecessor Pathfinder was performed.

2 The Bar Experiments
When Einstein predicted the existence of gravitational waves in his general relativity theory framework in 1915, he realized how extremely small the deformation of space-time, caused by any conceivable event in our universe, would be. For about half a century therefore, gravitational waves have been considered to be a purely academic topic, and nobody seriously dared to think about measuring these strange ripples in space-time.

2.1 The Bar Experiments of Joseph Weber
Against all mainstream thinking, Joseph Weber from the University of Maryland decided around 1960 to develop a detector for gravitational waves. His idea was ingeniously simple: a huge aluminium cylinder, 1.5 m long and 1.3 tons heavy, was suspended on a wire sling in vacuum, for isolation against mechanical and acoustical distortions. A gravitational wave falling perpendicularly onto the longitudinal axis of the cylinder would shorten and expand the cylinder at the frequency of the wave. When the frequency corresponds to the longitudinal eigenfrequency of the bar, oscillations will be excited. These oscillations should be observed with piezocrystals glued on the surface of the bar. In 1969, Joseph Weber claimed to have found pulses of gravitational waves. This was a great surprise for the physics community.

2.2 The Bar Experiments in Germany
At the Max Planck Institute for Astrophysics, which was still in Munich at that time, a series of seminars was held about that topic. From a theoretical point of view, Weber’s results must have had huge influence on the structure of the Milky Way, and scientists were very skeptical about it. Therefore, they decided to repeat Weber’s experiments under the leadership of Heinz Billing, and the work started in January 1971.
The setup was intended to be as close as possible to the original experiment so as not to affect comparability, but several improvements were implemented:
1. Weber glued the piezos all in parallel onto the surface of the bar. In Munich, we invented a particular structure of the piezo arrangement to put them partially in series. This “impedance matching” substantially improved the electrical noise background [3].
2. Weber used electronic tubes at the input of the amplifier. We replaced those with low noise field-effect transistors.
3. Weber looked for an increase in the bar’s oscillation energy. We looked for changes in amplitude and oscillation phase.
4. The theoreticians of the MPA developed an optimal signal evaluation procedure.

Together with a similar detector in Frascati, built by Karl Maischberger (soon a member of our group), this was the most sensitive room-temperature bar experiment at that time, run for three years. No signals were found [4]. Weber’s findings could not be confirmed despite of the significantly improved sensitivity.

3 Experimental Work in Germany / Interferometers

To further improve sensitivity, cooling was considered. But Robert Forward’s tabletop interferometers at the Hughes Laboratories and Rainer Weiss’s profound considerations of Michelson interferometers as detectors of gravitational waves had been known. Two substantial arguments were in favor of interferometers:

1. Bar detectors are sensitive only at their resonance frequency whereas interferometers are broadband.
2. Fundamental physical limits such as uncertainty relation or back action of the measurement onto the apparatus are less severe for interferometers because of their possible long baseline.

Therefore, the pioneering work on interferometers started in Munich in 1974.

3.1 Principle of Interferometers for GW Detection

Einstein described gravitational wave as a time-dependent strain in space: $h = \delta l / l$. In a Michelson interferometer which is hit perpendicularly by a gravitational wave, one arm is shortened during the first half period of the wave whereas the other arm is elongated. During the next half period, the sign changes. The wave therefore produces a time-dependent arm-length difference. This is exactly what is measured by a Michelson interferometer. For a given strain $h$, the quantity to be measured $\delta l$ increases proportional to $l$. It is therefore desirable to choose the light path $l$ for as long as possible. The optimum would be reached for half a wavelength of the gravitational wave. For signal frequencies of several hundred Hz, this would mean light paths of several hundred to 1000 km. To realize these huge light paths, Rainer Weiss proposed in 1972 to let the laser beam traverse the interferometer arm successively many times in the form of a Herriot optical delay line before it goes back to the beam splitter for superposition with the beam from the other arm. Other experiments use Fabry-Perots instead of delay lines; in this case, all beams are superposed on each other—also a viable solution. Therefore, the long light path seemed to be achievable, at least in principle.

4 Fight Against Noise Sources

The other question was the fight against all relevant noise sources when measuring $\delta l$. We decided to start with a small interferometer and to increase the light path in several steps. The first interferometer was fixed onto an aluminum cube of 30 cm side length. Then followed a setup with a 3 m arm length, and eventually a 30 m interferometer was implemented, both of them with optical delay lines to increase the light path. It was clear from the beginning that the interferometer had to be run inside a very stable high-vacuum system because of the refraction index fluctuation by thermal motions of the gas molecules or by outgassing processes.

4.1 Mechanical Noise

To isolate the optical components from seismic and acoustic noise, they have been suspended as pendulums. This turned out insufficient—and therefore, we introduced a multi-stage pendulum suspension. This is now standard in all highly sensitive interferometers. To keep the interferometer at its point of operation, we introduced a so-called local damping of the mirror motion. As a quiet reference, an individually suspended mass was used. Eventually, a feedback from the interferometer output to the mirror position was introduced.

4.2 Mechanical Thermal Noise

The Brownian thermal noise inside the optical components, especially the mirrors, modulates the light path and thus simulates a signal. It is therefore mandatory to use mirrors with low internal damping and keep the resonances out of the frequency regions of observation. We chose fused silica as substrate material; this is still in use nowadays. It turned out to be extremely difficult to avoid extra resonances or additional damping by fixing the mirrors to some holders. That led Karl Maischberger, a member of our group, to propose to suspend the bare mirrors in a wire sling. This was totally new and a big step forward.
In the later cooperation with the University of Glasgow, the suspension was optimized by choosing a monolithic arrangement. The mirrors hung on fused silica fibers, and fiber and mirror were connected through silicate bonding. Thus, no extra internal damping was introduced.

5 Noise from Laser Light

5.1 Frequency Noise
Frequency fluctuations of laser light produce a signal when two light beams with different light paths superpose. The light path in the two interferometer arms is normally quite different, and therefore, the laser frequency has to be very well stabilized. We did this in a series of approaches. The best solution turned out to be a stabilization relative to the total light path inside the interferometer. This is possible, as the gravitational wave signal appears as a path difference between the two arms. Even more complicated was the contribution of scattered light, as will be described in a following chapter.

5.2 Geometrical Noise of Laser Light
When operating our 3 m / 30 m prototypes, we were fairly close to the theoretical limit of sensitivity, the so-called shot-noise limit, given by the statistics of laser light. But there was a small contribution of extra noise, which we could not understand at all for quite some time. Geometrical fluctuations of the laser beam eventually turned out to be the source—totally unexpected and unknown at that time. To measure beam fluctuations, we used two photodiodes and sent half of the light to each diode. The difference between the signals provided a measure of position fluctuations. Our Ar-ion laser beam turned out to fluctuate in position by some $10^{-10}$ m / √Hz. A small misalignment of the beam splitter relative to the symmetry plane between the two arms coupled these lateral motions of the laser beam into a path difference between the two arms and thus into the output signal. To suppress these spurious signals, we invented a so-called mode cleaner [5]. The basic idea is to describe geometrical fluctuations of the laser beam, for instance, in position or orientation, as an addition of fluctuating higher-order laser modes. The mode cleaner is an optical resonator, resonant only for the fundamental laser mode. When sending the laser beam through the resonator, only the fundamental mode is transmitted, and higher-order modes are reflected. The transmitted beam is therefore as quiet as the quietly suspended optical resonator. This optical resonator also eliminates other unwanted light contributions. The mode cleaner is now standard in all GW interferometers.

5.3 Photon Statistics

5.3.1 Shot Noise
The signal of an interferometer increases proportional to the number $n$ of photons used whereas the statistical noise goes only with $\sqrt{n}$. For a given light power, this defines the shot-noise limit, a fundamental limit for the measurement. In 1985, our Garching 30 m interferometer reached the theoretical limit of the measurement, the first in the world to do so.

To meet the demands for more powerful and extremely stable lasers, the GEO600 team therefore developed and operated such lasers by themselves [6]. Currently, all interferometric gravitational wave detectors use lasers built by our colleagues in Hannover and implemented from there.

5.3.2 Power Recycling
In addition to using the strongest lasers available, it is also possible to recycle the light leaving the interferometer. This new idea was simultaneously proposed by Ron Drever (in Glasgow at that time) and Roland Schilling, a member of our group. For that purpose, the interferometer is run at a minimum of the light power at the signal output, and practically all light goes back to the laser. As seen from the laser, the interferometer acts like a mirror. When an extra mirror is inserted between the laser and the interferometer, an optical cavity is formed, and the light power can be considerably increased—by several orders of magnitude, limited by the losses inside the setup. This was the first time it was done with a Garching 30 m prototype with a suspended interferometer [7].

![Simplified optical layout of GEO600](image)

5.3.3 Squeezed States of Laser Light
The shot noise limit can be further improved by the use of properly prepared laser light, the so-called squeezed states. For this purpose, squeezed states are sent from the output port into the interferometer. By proper superposition with the main light, the shot noise at the output of the GEO600 detector could be reduced and the overall sensitivity enhanced [8]. This technique is also going to be used in the other detectors.

5.4 Signal Recycling
For signals lasting longer than the round-trip time of the light inside the interferometer, the signal can be enhanced by sending it back into the interferometer. This concept was proposed by Brian Meers from Glasgow. For that purpose, a Fabry-Perot is formed by using the whole interferometer like one mirror and an additional mirror at the output (see Fig. 5). The resonance frequency of this signal-recycling cavity can be chosen by the position of the recycling mirror and the signal enhancement by the transmission of that mirror. This arrangement is very versatile but also fairly complicated. In Garching, for the first time both recycling techniques have been used simultaneously in a so-called dual-recycling setup with a suspended interferometer [9]. A particular technique to effectively extract the signal from the interferometer.
by particular modulation techniques was developed and tested [10]. To match the dually recycled interferometer to particular signal frequencies, the Garching 30 m prototype was run in a properly detuned mode [11]. All these techniques have been installed in GEO600 and in the other detectors afterward.

5.5 Some Technical Problems

It is not possible to describe here the many conditions to be fulfilled to run an interferometer for the observation of gravitational waves. Therefore, only a few problems found out in Germany and techniques developed and implemented in GEO600 and later on in other detectors are mentioned.

5.5.1 Scattered Light

Scattered light is one of the most critical noise sources for very sensitive interferometers. We found it when experimenting with optical delay lines. First, we sent the laser beam through a small antireflective coated area of the coupling mirror into the delay line. A small fraction of the beam was still reflected and superposed with the output beam. The two contributions had a huge path difference, and frequency fluctuations of the light therefore modulated the phase of the beam—and thus produced an output signal.

Scattered light is produced when light is reflected at non-perfect surfaces or passes through components with areas of an inhomogenously distributed index of refraction. The wavefront of the beam is deformed, and light deviates from its ideal path. Thus, the laser beam is usually surrounded by a sort of halo of light with decreasing intensity for an increasing angle of deviation. When scattered light finds its way back into the main beam, it shifts the phase of the beam and thus gives rise to an interferometer signal.

Two typical examples:
Scattered light hits the tube walls of the vacuum system, is reflected onto a reflection spot of the main beam at the far mirror, and is scattered back into the beam. Motions of the tube walls thus couple into the interferometer signal. An example inside the delay line: The halo around the beam hits the area of another reflection and is scattered back into the beam reflected there. Again, there is a huge path difference between two interfering beams, and frequency fluctuations produce a signal. To suppress spurious signals introduced by scattered light, continuous careful work is needed, for instance, low scattering components and properly formed baffles with high absorption and vacuum compatibility. A comprehensive treatment of scattered light and relevant problems around optical delay lines can be found in the PhD thesis of Walter Winkler [12].

Squeezed vacuum signals and noise

For a quantum-mechanically correct description of an interferometer, one has to consider the superposition of two electromagnetic fields: the illuminating laser mode and the same mode entering the interferometer from the output port (Fig.6). The second mode usually contains no photon, but there is the ground state with energy content of ħω/2. In a simplified consideration there are two degrees of freedom of the field in question: amplitude and phase. By a specific preparation of the second input field, the so called squeezing, it is possible to reduce its uncertainty in phase by increasing the uncertainty in amplitude—or vice versa. When superposing a particularly squeezed field with the illuminating laser beam, it is possible to reduce the photon counting error in the output of the interferometer, by increasing the noise due to fluctuating radiation pressure onto the mirrors. The number of photons in the second input port is not important—in principle there need not to be any photon at all. Therefore the light entering the interferometer to reduce the photon counting error is called squeezed vacuum.
5.5.2 Thermal Effects in Optical Components

In the present detectors, the light power impinging onto the mirrors approaches 1 MW. Even tiny amounts of absorption cause huge effects by local heating of the components. The wavefront of the light beam is then deformed by reflection at a deformed surface or by thermal lensing when transmitted through some local inhomogeneously heated component [13]. To compensate such distortions, thermally adaptive optics has been developed and implemented in GEO600 [14].

Sometimes the shape of the surface of optical components needs to be corrected in different respects like radius of curvature or particular local deformations. To do so, the wave-front of a reflected laser beam is properly adjusted by measuring its deviation from a given reference, and locally heating the surface of the reflecting mirror in a fine grid of points [15]. This procedure has been implemented in GEO600. It is very versatile and can deal with most relevant imperfections.

5.5.3 Lock Acquisition

A huge number of servo systems is necessary to bring the interferometer to a particular point of operation and keep it there. The complicated technique is described in more detail in [16]. Wavefront sensing has been used in GEO600 to automatically align the interferometer and keep it at its point of operation [17]. As for electrostatic actuators, some feedback force needs to be applied to the interferometer mirrors to keep the interferometer at its point of operation. Magnets or other components attached to the mirrors spoil the mechanical quality factor of the substrate and couple to spurious electromagnetic fields. Applying forces electrostatically has been proven to be the most gentle procedure.

6 The Future

The observation of gravitational waves has started a fascinating new area of fundamental research, widening our knowledge about the world. We can look closer into the development of our universe, back to the big bang. To arrive there, many contributions from different sides have been necessary, especially those from the members of GEO600.

To increase the sensitivity of the detectors, research is ongoing in many fields—more laser power, improvement of the light recycling techniques, the use of squeezed states going in many fields—more laser power, improvement of蓬勃发展 of our universe, back to the big bang. To arrive knowledge about the world. We can look closer into the developing new area of fundamental research, widening our knowledge about the world. We can look closer into the development of our universe, back to the big bang. To arrive there, many contributions from different sides have been necessary, especially those from the members of GEO600.

Walter Winkler started in 1971 at the Max-Planck Institute for Astrophysics to construct and operate a Weber bar detector and afterwards a prototype interferometric detector for gravitational waves. He continued this research at the Max-Planck Institute for Quantum Optics and eventually at the Max-Planck Institute for Gravitational Physics. He was significantly involved in designing and constructing GEO600. He was for a long time member of the LISA study team and of the Scientific and Technical Advisory Committee for VIRGO.