Report to the National Science Foundation

by the

Panel on Interferometric Observatories for Gravitational Waves

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INTRODUCTION

The workshop on Gravitational Wave Physics and Astronomy was convened at Cambridge, Mass. on November 10-14, 1986 to coordinate information and review the state of developments in that field with particular attention to the plans for the Laser Interferometer Gravitational Wave Observatory (LIGO) Project. This workshop consisted of specialized consultants from various relevant fields and was attended by approximately 55 individuals including scientists from Britain, France, Germany and the United States. Attached in Appendix A is a list of the NSF panel members, workshop participants, consultants and observers. The charge to the Panel is also included as Appendix B.

The workshop program (displayed in Appendix C) was very intensive, but broad ranging. The quality of the presentations was excellent and it was especially gratifying to note the high competence and enthusiastic interest of both the foreign participants and the specialists from various laboratories and industrial organizations. The panel thanks the Caltech group and the MIT group for their patient tutelege while describing the LIGO project and particularly thanks Prof. Weiss, and his associates, for their hospitality and efforts to provide the support and organization for a highly successful workshop.

The following pages constitute the report of the Panel; a summary of our recommendations may be found in the last section.

1. THE SCIENTIFIC CASE

A. The Importance of Successfully Detecting Gravitational Waves

Einstein's theory of General Relativity is now 70 years old. It has survived numerous challenges, and is still our most successful theory of gravity. However, experimental tests of the theory are largely confined to slow-motion, weak-field situations. An analogy with electromagnetism would be that we believed in Maxwell's equations because of their elegance, but that we had actually only verified the theory for electric fields, and only in the quasi-static limit. We have no direct experimental data on the gravitational analogues of magnetic fields and of electromagnetic radiation.

Gravitation differs from electromagnetism in an important way: it is a nonlinear theory. The famous perihelion shift of Mercury is a test of this nonlinearity, but only as a weak-field correction to Newtonian gravity. Some of the most remarkable predictions of the full nonlinear theory, such as black holes, have no direct experimental confirmation as yet.

The scientific motivation for searching for gravitational waves thus has two equally important components:

(1) It will test fundamental predictions of General Relativity that cannot be tested in any other way.

(2) Successful detection will open a new astronomy in the same way that radio waves and X-rays opened up new windows on the Universe.

General Relativity makes specific predictions about the nature of gravitational waves. For example, they propagate at exactly the speed of light, and they have the polarization properties of a spin-2 field. Other theories of gravity generally differ in one or both of these predictions. Detection of a burst of gravitational waves from a supernova in the Virgo cluster of galaxies 4×10^7 light years away (13 Mpc), together with optical identification of the supernova, which can be done within a few days of the event, would test the equality of the propagation speeds of light and gravity to about 10^{-10}. Simultaneous observations of gravitational wave bursts at 3 or 4 detectors spread around the earth would enable the polarization properties to be determined.

The gravitational interaction is so weak that there is no hope of laboratory production of waves. We must rely on astrophysical phenomena that involve the coherent motion of large masses at relativistic speeds. Thus successful detection enables one to study the astrophysical sources. Moreover, one obtains information essentially orthogonal to what one learns from electromagnetic radiation. Gravitational waves may be the *only* way to study objects such as black holes directly.

B. Sources of Gravitational Waves

There is a large literature on possible sources of gravitational waves, and there is a strong theoretical program to calculate detailed amplitudes and waveforms, and to estimate event rates. These results can be used to estimate the sensitivity required to detect the waves.

Sources can be divided into three categories:

1) Burst sources
2) Periodic sources
3) Stochastic sources

From the many possible sources in each category, we mention a few examples.

A typical example of a burst source is emission from a supernova collapse. The strength of the wave can be characterized by the dimensionless strain $h = \Delta L/L$ induced in the detector, where L is the length of the detector and ΔL the change in the length. The amplitude is approximately

$$h \approx 5 \times 10^{-22} \left[\frac{\Delta E/M_{\odot}c^2}{10^{-3}}\right]^{1/2} \left[\frac{15 Mpc}{r}\right] \left[\frac{1kHz}{f}\right]^{1/2} .$$

Here $\Delta E/M_{\odot}c^2$ is the efficiency of the event, the fraction of a solar rest mass of energy carried off by the waves, r is the distance, and f is the frequency of the peak of the spectrum. A supernova with this efficiency of 0.1%, in our Galaxy, $r \approx 15$ kpc, would produce an h within a factor of 10 of the sensitivity of currently operating laser interferometers. Unfortunately the supernova rate in our Galaxy is probably only one every 30 years, and one has to go out to a distance of about 15 Mpc before the event rate is about one per month, producing this standard signal of $h \approx 5 \times 10^{-22}$, some 10^4 times smaller than can be detected by currently operating laser interferometers. Moreover, the efficiency of such events for producing gravitational waves is not known, and may be much smaller than 10^{-3}.

An example of a source where the efficiency is known very well is the spiraling in and coalescence of two orbiting neutron stars as they lose energy from their orbit by gravitational wave emission. During the last few seconds of its lifetime, such a binary system produces a roughly sinusoidal "chirp" of radiation that sweeps up in frequency from a few hundred Hz to about 1 kHz. One can estimate the rate of such events from the observed statistics of precursor binary systems in our own Galaxy. Such an estimate suggests that out to a distance of about 100 Mpc there should be several events per year, with an effective amplitude $h \approx 10^{-22}$. Most importantly, the event rate scales with the volume of the Universe one observes, i.e. with h^3. Even if the estimate of the event rate is off by a factor of 1000, an effective detector sensitivity of $h \approx 10^{-23}$ would be extremely likely to lead to a positive detection of gravitational waves. Fig. 1 shows estimates of amplitudes from several possible burst sources. The signal strengths for burst sources shown in the figure are given in h_{rms} times $\sqrt{n}$, where n is the number of oscillations in the burst. The signals from some burst sources, particularly coalescing binaries, are quasi-periodic so that the optimal filter for detecting these events would search for a wave train of n oscillations. The detection signal to noise can therefore be improved by approximately $\sqrt{n}$.

Periodic sources include waves from slight asymmetries in rotating pulsars. Successful detection, or the setting of upper limits because of the absence of asymmetries, would give valuable information about the physics of neutron stars.

Stochastic radiation is a cosmological background produced during very early epochs in the Universe. Detection, or setting of upper limits, provides a test of ideas in fundamental physics, such as Grand Unified Theories, cosmic strings, and the Inflationary Universe.

C. Other Activity

Groups in Britain, France and Germany are also proceeding with plans to build detectors of comparable scale to the facility proposed for the U.S. Such a network is important for the ultimate scientific usefulness of the project.

D. Summary

There is great difficulty in reliably predicting the detector sensitivity required to guarantee success of detection. The uncertainty comes from poor knowledge of the statistics of the sources, or of the strength of the waves from known sources, or both. There is a good chance that the first sources to be discovered will be something we have not even thought of.

At the sensitivity of the simple first detector envisaged, $h \approx 10^{-20}$ for burst sources, we believe there is a small but not zero probability of detection. At the level of the more advanced detectors, $h \approx 10^{-22} - 10^{-23}$, we believe that there is a strong probability of detection. Moreover, the information gained by a wide-band receiver like a laser interferometer would enable one to do physics and study the sources, and not simply report the detection of glitches. The detection of gravitational waves would be likely to bring about a revolution in our view of the universe.

2. DETECTORS

A gravitational wave causes a quadrupolar strain h to be developed in the detector with a magnitude depending on the particular source that can range between 10^{-24} up to 10^{-19}. The detection of such an incredibly small strain has been the major challenge addressed by gravitational wave astronomy for the last 20 years. The pioneering work was done using the original technique, invented by J. Weber, of detecting the resonant ringing of a large (~ 1 ton) aluminum bar. Such detectors have been able to achieve a sensitivity of 10^{-18} for broad-band bursts that have substantial power in the neighborhood of 900 Hz. A potential improvement of as much as 100 may be still possible in such detectors giving them an excellent sensitivity for broad-band bursts near 900 Hz. However, because of their narrow-band response, such detectors cannot reveal the details of the burst's waveform; for that a broad-band detector is required.

During the one week workshop the Panel heard plans for a broad-band detector facility called LIGO. The technique that has been developed over the last eight years involves an interferometer with two arms of 4 km length. If the arms are oriented along the x,y axes and a plane gravitational wave of this polarization traveling along the z axis is incident on the instrument, one arm will be shortened and the other lengthened. The resulting fringe shift represents the output signal. However, since the frequencies of interest are in the region 100 Hz to 1000 Hz, it is clear that the sensitivity of the instrument would be greatly enhanced if the interaction time between the light and gravity wave could be extended from the round-trip transit time in the arms, of order tens of microseconds to times of order 1 millisecond.

One technique used to accomplish this is to use large mirrors at each end of the interferometer arms and cause a well collimated laser beam of 0.5μ light to make multiple bounces before exiting the system and interfering with light from the other arm. One hundred bounces increases the interaction time and hence the fringe shift by the same amount. This technique is called the "delay line mode" of the Michelson interferometer and requires large mirrors and accurate control of the mirror figure in order to cause the beam to enter and exit the apparatus correctly. An alternative scheme involves using Fabry-Perot mirrors and injecting the light directly through the mirror surface. The mirrors form an optical cavity and the extended interaction time between the light and the gravitational wave is achieved by multiple bounces of the light between the mirrors. The Fabry-Perot approach requires a highly stable laser and, if light is to be recycled (section 3 below), further work is required on techniques to equalize the interaction times and recombine the beams.

Both of these techniques are being considered for the phase I detector and the particular problems associated with each scheme will be investigated during the Engineering Design Study planned for the next year with the goal of meeting the sensitivity shown in Fig. 2 for the phase I detector.

The question naturally arises of whether or not these design goals can be realized starting from the present experimental base. Fig. 3 is an attempt to show the progress with detectors over the last eight years. The spectral displacement $x(f)$ in meters/$\sqrt{Hz}$ is shown as a function of time for the four groups doing work. The Munich and MIT detectors use the Michelson delay line technique while the Caltech and Glasgow detectors use the Fabry-Perot configuration. The phase I detector involves an extrapolation by a factor of 4 of the displacement sensitivity achieved by the present Munich instrument. A factor of 4 increase seems reasonable in view of Fig. 3 which shows a factor of 3 per year for the existing instruments. Also in Fig. 3 is shown the necessary improvements in the Caltech and MIT detectors needed to reach the Phase I goal. This coupled with the factor of 100 in length would give the sensitivity curve shown for the phase I detector. Future increases in sensitivity necessary for the phase II detector are discussed in Section 3.

The operation of a facility, especially one involving a considerable investment, requires good diagnostic techniques for quickly determining unusual sources of noise or detector malfunction. Diagnostic techniques must be automated and test proceedures for verifying performance must be an integral part of the system design.

Good diagnostics will help minimize downtime in the event of failures. But high reliability is most important in achieving maximum utilization of an observatory. Many of the techniques which have been developed for laboratory use must be redesigned for long-term unattended performance and for care and maintenance by personnel who were not involved in their development.

An important feature of the proposed program is the construction and simultaneous operation under one management of two widely separated but otherwise identical detectors. The separation minimizes the effect of extraneous seismic or other noise sources. There was an overwhelming consensus at the workshop that it is imperative that coincidence techniques be used to verify the observation of a signal.

Simple observation of a signal is not sufficient for the viability of the project, and work is underway at several centers on the problem of extracting physics from the observations. At the simplest level two detectors enhance the believability of a signal and also define a circle on the sky containing the source. A minimum of four detectors is required to determine the direction of the source and the wave form in its two polarization states. For the ultimate extraction of all the information contained in a signal, a network of stations with the enhanced sensitivity of the phase II detectors and distributed around the world will be necessary. The goal of phase I is to construct a facility with the ability to extract a signal from the noise with a high degree of believability and to form a basis for a more advanced instrument. The enhancements possible are discussed in Section 3.

3. EXPECTED IMPROVEMENTS

The proposed gravity wave detection system depends on sensitive coherent optical techniques, which are being stretched to their very limits by the extreme demands of this application. Fortunately other fields are driving the technology forward also. Optoelectronics is in a state of unprecedented development and explosive expansion driven largely by new technical capabilities and by other applications in laser communications, fiber optics, rotation sensing, coherent laser radars, materials processing, etc. These fields also need improved optical coating techniques, optical modulators with lower losses, optical fibers of higher power carrying capability, and solid state lasers of improved efficiency and reliability. There also has been an enormously stimulating effect of the gravity wave detector challenge on the laser and quantum optics field. These almost insuperable demands have led directly to new photon measurement concepts such as quantum non-demolition detection and have strongly fueled the experimental race to demonstrate so called "squeezed" radiation states. We turn now to sketching a likely scenario in which hard work and clever ideas and devices from within and from outside the gravity wave community will lead to major sensitivity enhancements.

A. Lasers

We expect that the first detectors will be installed with argon ion lasers as the sources, probably operating on the 514 nm line. The system may deploy 3 to 5 such lasers to produce approximately 20 watts of single-mode single-frequency power using a coherent power addition scheme (optical phase lock) recently demonstrated in France. This laser system, along with modest improvements of the frequency locking techniques already used in prototype systems, is expected to lead to gravity wave detection sensitivity levels as indicated in Fig. 2 by the upper line marked "Phase I detectors". The 20 watts of laser light assumed here will require a power consumption of about 120 kW corresponding to a power efficiency somewhat above 10^{-4}. With a plasma tube life expectancy of approximately 2000 hrs, about 10 replacement tubes may be required per year at an annual cost of perhaps $100 k.

Since increasing the laser power is one of the clear ways toward still higher detector sensitivity, it is appropriate to weigh contemporary advances in solid state lasers of significantly higher power efficiency. The most well developed alternative candidate at this time is the Nd^{3+}:YAG laser emitting at 1.06 micron wavelength. Commercial laser units, based on a single YAG crystal can produce 300 W cw power with long operating lifetimes. Present units are intended for cutting and metal working applications, and the spatial quality of their beams is unfortunately far from the diffraction limited beam needed by the gravity wave program. Still the wall-plug efficiency is several percent and this fact alone makes it interesting to consider further. One can forsee obtaining beams of high quality at the 100 W level from such devices by several optical techniques such as unstable resonators, wavefront conjugation and/or holographic mode converters. The high frequency stability required could be obtained by injecting (into a power amplifier or oscillator) the low power beams from a monolithic Nd:YAG pumped by a diode laser. Intermediate power amplifiers, if needed, could also be diode pumped. Indeed, there are rumors that diode laser pumped Nd devices at the 300 W level are being developed for another national program. Their projected reliability and power efficiency in the 25% range would be a welcome contrast to the Ar^+ case.

It seems certain that other solid state laser materials may also suggest themselves for enhancing the detector systems. For example, multi-hundred watt units based on Alexandrite also are produced commercially, but would need significant development to work as well as Nd:YAG. One possibly interesting difference is that the Alexandrite wavelength (0.73 to 0.79 micron) may be usable directly for the interferometer, whereas the Nd laser would probably require conversion to the second harmonic at 530 nm by means of a nonlinear crystal. Recent progress in growing damage-free $LiNbO_3$ may make frequency doubling a simple project, using an external resonator. New nonlinear crystals being developed in China (β-$BaBO_3$) may also be of interest in this regard.

Lacking a reliable high efficiency frequency doubler, the Nd laser system perhaps loses some of its appeal since the longer wavelength reduces the sensitivity somewhat and also requires larger diameter light beams. This point could be a critical issue if the delay line geometry is selected. We anticipate that the observatory cooling system will be designed at the 300 kW level to accomodate a reasonable bank of argon lasers – say 10. But with good luck, suitable high-efficiency solid state sources will be available at the appropriate time; if not, additional cooling can then be installed.

B. Advances in Interferometer Design

A resourceful invention to reuse the valuable laser light has been suggested by Drever. The "recycling" concept may be understood along these lines; the input power is divided equally and sent into the two interferometer arms. The beam recombiner will be operated so that the two equal outputs from the interferometer arms will be phased to interfere destructively in the direction toward the photodetector. Then this beam can contain the minimum shot noise contribution, leaving mainly the local oscillator sidebands used for detection plus the residual arm imbalance signal which will contain the potential gravity wave information. Since the beam recombiner is non-absorbing, the rather significant power returned from the two interferometer arms is not dissipated, but is instead steered by the beam recombiner back toward the laser source. An attractive idea is to "recycle" this light by placing an auxiliary mirror in the input line to return this unused light into the experiment. The storage time in the two arms would be set appropriate to the desired system time response, while the input reflector would be chosen to produce the largest circulating power inside this auxiliary interferometer. With contemporary low-loss mirrors, as used typically in laser gyroscope applications, substantial power enhancements should be possible. Enhancing the power 10-fold or more should in principle reduce the shot noise level 3-fold, but – of course – the recycling interferometer adds another interferometric condition which will have to be servo-controlled with exquisite quality just to reach again the original noise level and then 3-fold better.

Another interesting idea has been proposed to enhance the sensitivity in looking for periodic sources. With long interferometer arms and low-loss mirrors, one can store the light much longer than a half-period of the gravity waves, and thus reduce the detected signal. Drever has suggested that one should switch the light between the two arms after a time approximately $\tau_p/2$, where τ_p is the period of the source in question. In this way the signal sideband grows with the number of exchanges, scaling with the photon storage time in the total system. This "resonant recycling" can be achieved also with Fabry-Perot arms in the main interferometer by using appropriate optical circulators based on polarization or Faraday rotation.

One might at first worry that the mirrors in the Fabry-Perot system will be exposed to powers approaching 100 kW. The intensity however is far below the values safely used in the Ar^+ laser itself. The problem may rather come with mirror figure distortion by the absorption of several watts over the $\approx$ 100 cm^2 mirror coatings, making a high thermal conductivity material such as sapphire attractive as the mirror substrate. Sapphire is also a material of choice mechanically speaking, because its high sound velocity pushes the mirror resonance toward higher frequencies and the high Q further reduces the below-resonance broad-band thermal noise. Finally, it has recently been found that sapphire can be optically polished very well, with rms surface roughness in the < 5 Angstrom domain, which may lead to mirrors of even lower loss.

In summary, innovative reuse of the precious laser light will almost surely lead to a power gain of 100-fold, assuming no insuperable new problems develop. A major challenge will be to identify and remove the unwelcome new noise sources, so as to regain, and then surpass, the previous interferometric sensitivity level.

C. Seismic Isolation

Sensitivity increases in the interferometer system will require corresponding progress in other sensitivity limiting areas before dramatic progress will be obtained. For example, vibration and seismic isolation is one area of interest for improvements of system sensitivity, particularly at the lower frequencies (100 Hz and lower) associated with the coalescing binary neutron star source model.

The effectiveness of seismic and acoustic isolation has been impressive and adequate to date. A number of techniques are proven in the field. They include pneumatic isolation, multi-pole filters made with stacks of steel and rubber and quiet electronic feedback for damping the natural behaviour of high Q suspensions in which the lossiness has been minimized to reduce thermal noise of the test masses. To reach the advanced levels of performance significant improvement must be made. It appears that combinations of these techniques may be sufficient but they must be optimized. A staged design approach to minimize passive damping in the innermost portion seems advantageous. Each stage of isolation, starting from the inside and working out, incorporates more passive damping and more robust technology. Built-in testing to verify that the isolation is fully functional should be considered.

Continuing this line of research may pay handsome dividends in the expected long term growth toward sensitivity improvement at the lower frequencies.

D. "Squeezed" States in Interferometry

Of course the quest for further sensitivity enhancements will continue. One fascinating recent development in quantum optics may well turn out to have the potential for a "breakthrough" level of sensitivity advance. This subject is called "squeezed" states and is concerned with the organization of the zero point oscillations of a radiation mode by nonlinear optical interactions. Its significance for gravity wave detectors can be explained with the help of a simple picture of the photodetector's shot noise as given by Caves. He views the shot noise as a consequence of "heterodyne" detection by the coherent laser "local oscillator" field of the vacuum field with the same wavelength and spatial and polarization mode as the coherent laser field. With rf analysis of the photocurrent fluctuations one is seeing the down-converted noise from two symmetrical windows in the optical domain (the "signal" and "idler" bands). The observed rf signal is essentially the superposition of two zero point vacuum fields. Relative to the laser field these "noise sidebands" would represent amplitude modulation. It has long been predicted by Walls, Shapiro and others that nonlinear interactions in a degenerate optical parametric amplifier could produce noise sidebands organized as mainly FM sidebands with correspondingly reduced AM sidebands relative to 1/2 the pump input frequency. Such noise light would be called "squeezed" light since the former excursions in the AM sidebands have been squeezed into the FM sidebands. In very recent work Kimble and his associates have produced a dark "squeezed" vacuum state which is 4 dB "darker than dark" in its AM quadrature. The noise has been increased by a corresponding factor in the other quadrature. Caves suggested that it would be interesting to inject a beam of such AM "squeezed" light into the gravity wave interferometer beam divider, arranged to be optically conjugate to the high power beam already present. Theory predicts sensitivity improvements (relative to the shot noise part of the system noise) will be achieved by reduction of the detector noise level. Ten times "squeezing" may not be easy to achieve, but it still may be easier than a corresponding 10 times increase in laser power to obtain the same sensitivity gain.

Even without "squeezing", when these projected improvements in sensitivity are taken along with a reduction of the seismic noise by improvements discussed above, one could anticipate vastly improved observatory sensitivity for gravity wave radiation. A possible projected sensitivity curve is indicated in Fig. 2 by the lower line labelled Phase II. The optimum sensitivity will be in the range $h \approx 10^{-23}$. The exciting and highly significant science which this sensitivity would allow has been described in Section I.

4. COMMENTS, ADVICE, CONCERNS ON THE LIGO STRATEGY

A. Site Location

Many elements should influence the choice of a site. Considerations must be given to proximity to the university, transportation convenience, infra-structure, simplicity and cost of construction, seismic quietness, etc. The panel is particularly impressed with the importance of an existing infra-structure (the presence of a stock room, quick repairs of a VAX, etc). We recommend that a re-examination be made of the proposed State of Maine site, which seems to be lacking important qualities.

B. Two Sites

Test signals to verify performance need to be available at as many levels as possible. We support the development, at each site, of interferometers of different length which will aid in the identification of false signals. Two sites which are separated by at least 1000 km are essential to identify correlated signals that have a high enough probability to warrant detailed evaluation. We strongly support the philosophy of two sites with identical, or closely similar, detectors.

C. Facility Size

We note that the extragalactic event rate goes as L^3, where L is the length of a detector arm; while the cost of a facility goes less than linearly with L because of end station and other length independent costs such as the engineering, buildings, receiver systems, etc. Thus $L = 1$ km, as compared with $L = 4$ km would have an event rate of 1/64 of the proposed facility.

We support full authorization of the 4 km by 4 km facility, but note that staged construction and milestones with, for example, interferometers first operating at 1 km by 1 km, will lead to a more uniform funding profile and a smaller staff pulse. The construction cost may be more, but the real cost in discounted present value of the expenditure will be less.

D. Oversight Committee

We recommend that the presidents of Caltech and MIT jointly appoint an oversight committee which reports to them. The committee should have nationwide and international participation and be charged with overview of the scientific program, management of the facility and facility availability to outside scientific groups.

We recommend that this committee meet at least twice a year during the construction phase and that copies of their reports be given to the NSF.

E. Project Director

The panel recommends that the project be headed by a director of scientific and engineering stature comparable to the oversight committee members and the investigators. This director must be the final and single authority for decisions during construction and evolution into an operating observatory. Management by a steering group may have been adequate until now, but would not be appropriate for the construction and operation of a project of this size.

F. University Involvement

We note that the faculty involvement at Caltech and MIT in this project is minimal and recommend that their involvement be significantly increased by at least one more faculty position at each university.

G. Choice of the First Detector

We recommend that the choice of type of the first detector and its associated laser be made prior to submission of the construction proposal. We feel it is important to be specific about the configuration and sensitivity of the initial detector and that the present research program be directed toward establishing that the necessary hardware can be constructed in a timely fashion.

H. Continued Research on Advanced Detectors

It is important to develop advanced detectors and therefore that research continue to this end.

I. Facility Flexibility

We believe that it is very important to build the facility so that more vacuum pipes can be added to it at a later stage if this is desirable. Conversely, we believe that the facility in its first stage, should have a <u>single</u> vacuum pipe of adequate size. We believe that even at the start of the project a number of interferometers are desirable (to remove spurious signals).

J. Construction Strategy

We recommend continued examination of less expensive approaches to vacuum, construction and fabrication techniques. We note that a good architectural & engineering firm will do just that. Although we recommend continued attention to cost saving methods, we do *not* recommend a delay to the project for this purpose.

K. Operating Costs

We note that the observatory will cost at least $3M/yr for operation. In addition the groups at Caltech and MIT require continued funding so that they may develop ever more sensitive detectors. The cost of these groups is currently $3M/yr. In addition the observatory will surely spawn new groups and there is in addition, the cost of data analysis; the sum costing (at least) $3M/yr. In short, the NSF needs to plan on an operating budget for gravity waves in the 90's of (about) $10M/yr.

5. SUMMARY

A) A strong case has been made for the scientific value of the goals of the project.

B) Though there are large uncertainties associated with the strengths of the many different kinds of astrophysical sources and the ultimate capability of interferometric detectors, there is a high probability that this facility will ultimately provide for a giant leap in our understanding of the gravitational force, one of the most fundamental forces of nature, as well as our knowledge of astrophysical phenomena.

C) It is anticipated that this facility would uniquely provide the most sensitive and certain prospect for detecting astrophysical events and identifying their nature. Essential to this capability is the twin nature of the two interferometers. Though companion efforts in other countries are highly desirable, a common management of the two LIGO detectors is important both for the coordination of the observational program and for the analysis and identification of observed events. This facility would provide for a continued and thriving development of the field.

D) It is important to proceed directly to the construction of a long baseline interferometer in a timely manner since many aspects of the detector development program cannot otherwise be tested.

E) The rate of detectable extragalactic events increases as the cube of the interferometer sensitivity, thus putting a high premium on the long baseline. Though a multistage, or phased authorization to the final configuration was carefully considered, the panel does *not* recommend this approach. We recommend full authorization with phased construction and appropriate milestones.

F) The plans as described in the presentations and in the various documents provided appear to be well conceived. The procedure which has been employed in drawing up the existing designs and in making the cost estimates appears reasonable and adequate for proceeding to the final design for submission. Effort should continue to examine design alternatives which may decrease costs, particularly in the area of the vacuum system and enclosure. We do not recommend that the project be delayed by this process of re-examination. It is important to make the choice between Fabry-Perot and Michelson interferometer type detectors before submission of the final design. However, it remains important to develop advanced detectors and therefore research should continue to this end.

G) Because of the magnitude and dual nature of the facility, with laboratory sites widely separated, it is especially important that the construction and operation be well managed. The panel feels that the project requires a single scientific project leader of high stature to direct the activities. Efforts should immediately be directed to providing such leadership.

H) In looking forward to the utilization of the facilities it should be recognized that in addition to a budget for its operation, adequate funds will be required to support both the needs of experimental groups and further detector development.

I) In conclusion, the panel enthusiastically supports this development effort and urges that the plans for the project be refined along the lines indicated and that the design be completed. We recommend, then, that the construction project be brought to the National Science Foundation Board for consideration and (hopefully) for funding.

Panel Members:

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Val L. Fitch	Andrew M. Sessler
Richard L. Garwin	Saul A. Teukolsky
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Figure 1

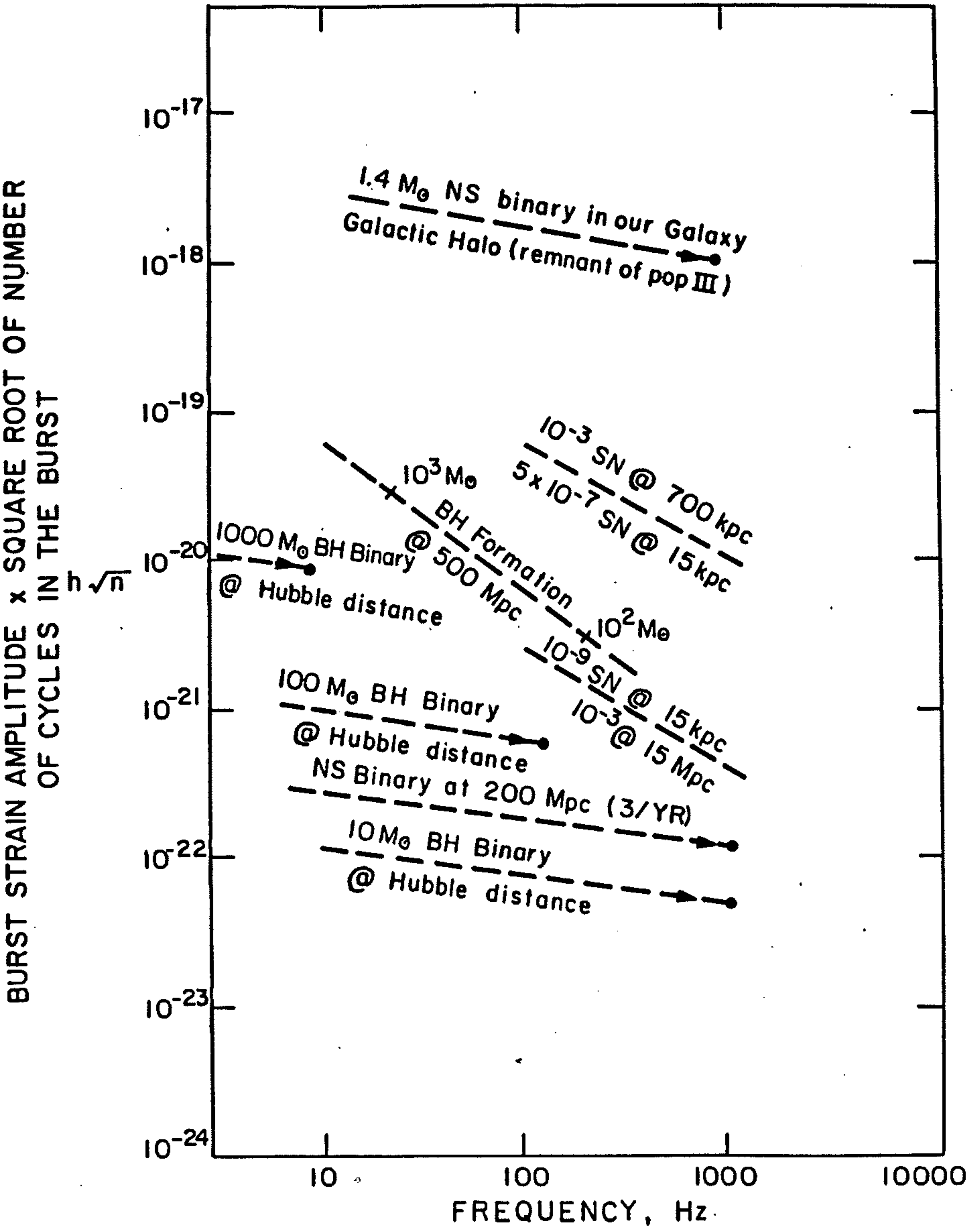
The figure shows estimates for the rms strain amplitude spectra of four types of burst sources. The amplitude is given for a detection bandwidth approximately equal to the frequency. The estimates for supernova explosions (SN) assume a signal to noise of 5 and indicate the conversion efficiency of total rest mass to gravitational radiation assumed as well as the distance to the explosion. The event rate to a distance of 15 Mpc is expected to be several per year. The conversion efficiency is uncertain. The signals from black hole formation (BH) are estimated for a distance of 500 Mpc. The rate is unknown but the amplitude spectrum is completely determined by General Relativity and varies with the mass of the hole as indicated. The lines with arrows terminating at a high frequency point are chirp spectra of coalescing compact binary systems. The strain amplitude of the chirp sources has been multiplied by the square root of the number of cycles which the source spends in the vicinity of each frequency. The amplitude spectra are securely estimated; however the rates for black hole binary systems are unknown. The coalescence of neutron star binaries (NS) are estimated for two cases. The lower curve is a conservative estimate for the number of events in nearby galaxies, based on the number of neutron star binaries discovered in our Galaxy. Both the event rate and the amplitude for this signal are well determined. The higher curve is based on a highly speculative model which assumes that the dark matter in the halo of our Galaxy consists of remnants of an early population of stars.

Figure 2

The figure shows the present sensitivity of both cryogenic narrow band bar and prototype interferometer gravitational wave detectors. Projections for the sensitivity of interferometers operating in the 4 kilometer baseline systems are given for various assumptions. The upper curves, labeled phase 1 detectors, indicate the projected performance of interferometers based on current experimental practice but with improvements in displacement sensitivity by a factor of 3 and extension to 4 kilometers. The lower curve of the set showing phase 1 detector projections assumes a further factor of 3 improvement in displacement sensitivity and anticipated improvements in seismic isolation over present systems. The lower curves, labelled phase 2 detectors, incorporate the light recycling scheme described in the text and substantial improvements in seismic isolation techniques over those used in present practice. The effective demonstration and tests of the light recycling systems will require the long baseline system.

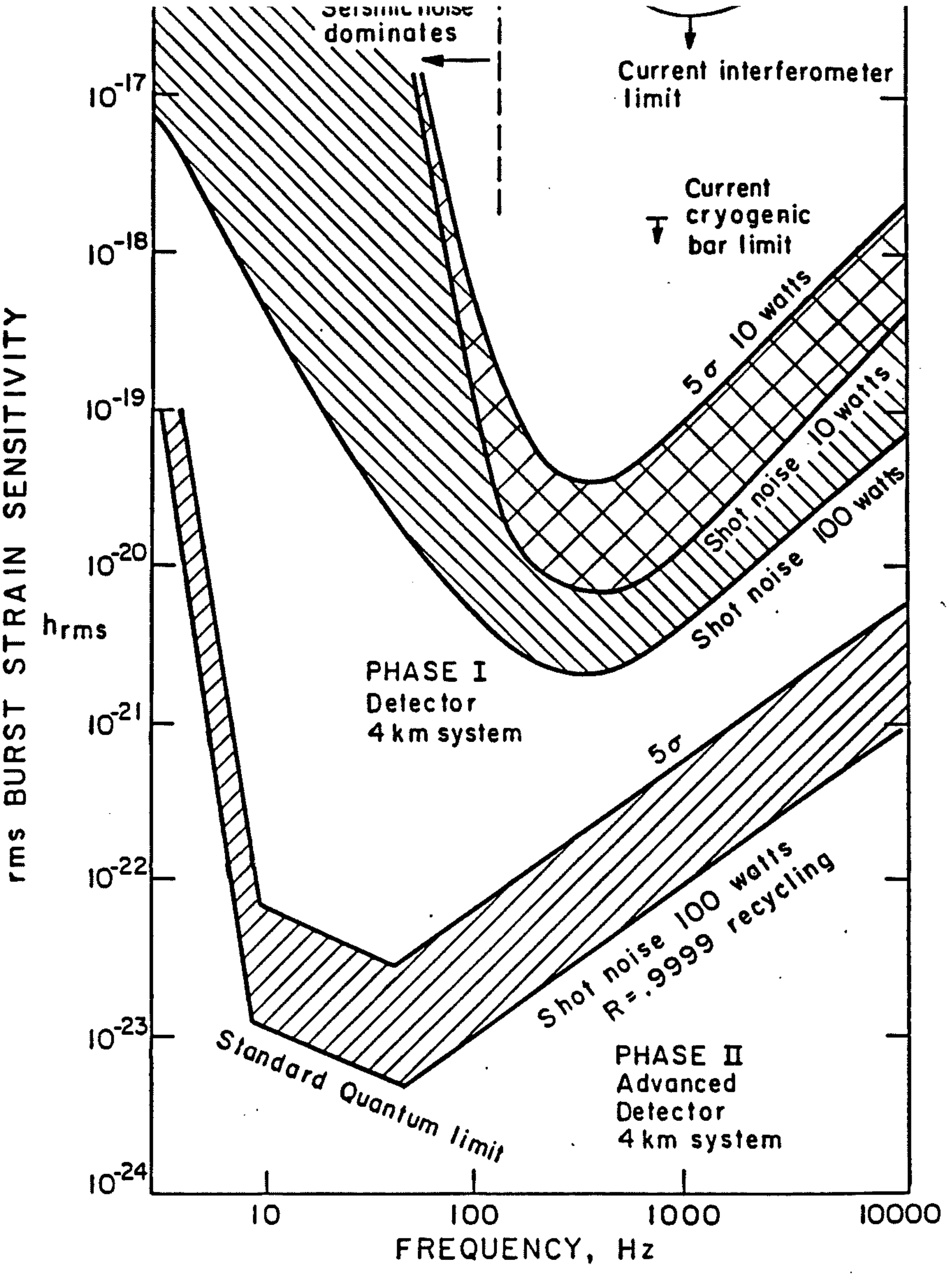
Figure 3

History of the root-mean-square noise in interferometric gravity-wave detectors. The upper figure shows the displacement noise at a frequency of 2 kHz for the Munich 3 meter, Munich 30 meter, Glasgow 10 meter, MIT 1 meter, and Caltech 40 meter detectors. In the early years the noise was much worse at low frequencies than at high – so much worse that Caltech did not even record the noise level below 2 kHz (which is why this figure is shown for 2 kHz). At present the noise spectrum at Caltech is nearly flat from 500 Hz with a minimum (marked "Caltech ▲") at 950 Hz; the spectra at Munich and Glasgow are nearly flat above 1 kHz; and the spectrum at MIT continues to fall with increasing frequency, reaching the level marked "MIT ▲" at 5 kHz. The lower figure shows the rms noise (i.e. the one-sigma sensitivity) for the amplitude h of a broad-band gravitational wave near 1 kHz interacting with the longest of the interferometric detectors (Munich and Caltech), and with the world's best bar detectors.



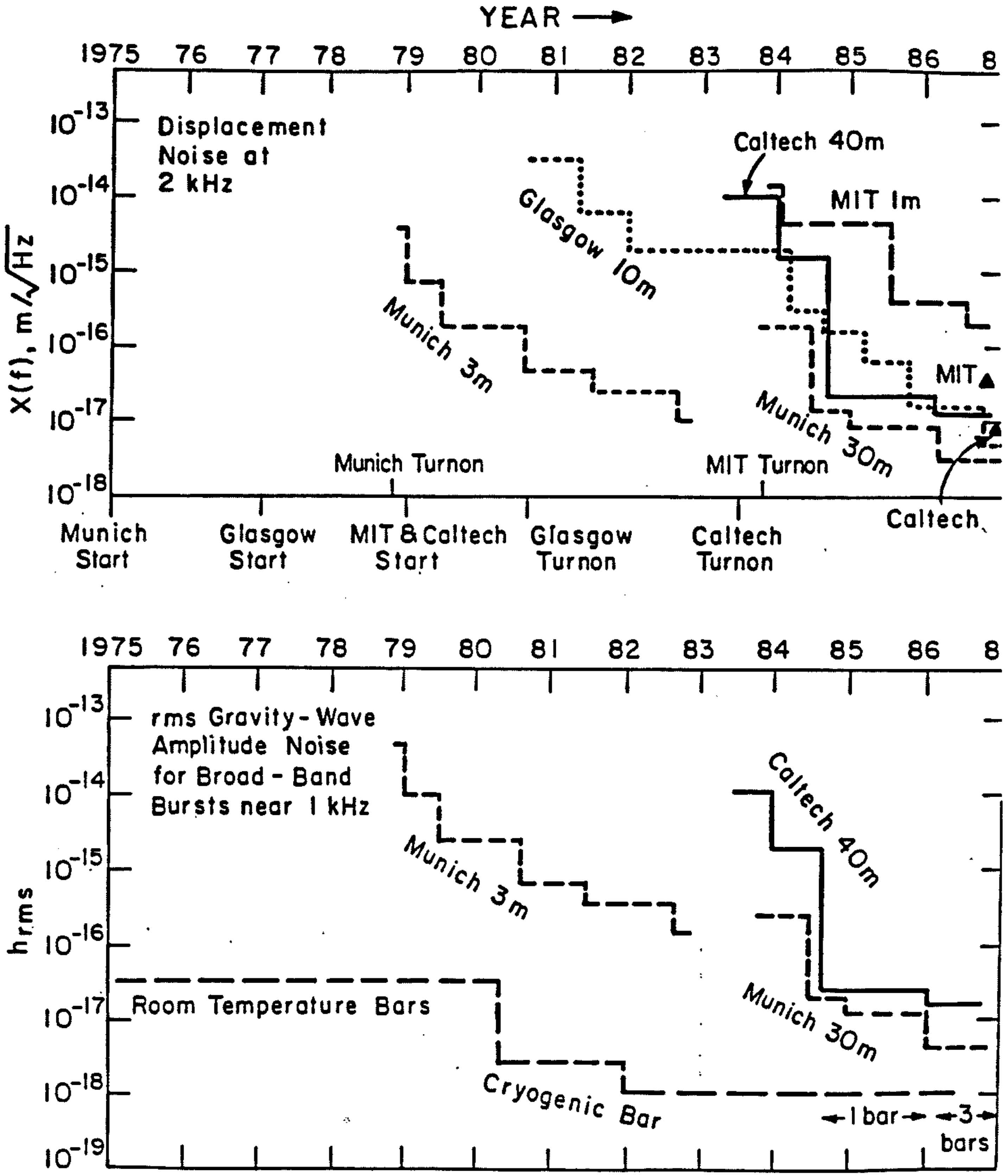
STRAIN SIGNAL ESTIMATES FOR BURST SOURCES

Figure 1



PRESENT AND PROJECTED BURST STRAIN SENSITIVITY

Figure 2



SENSITIVITY AS A FUNCTION OF TIME

Figure 3

(amended Nov 15,1986) Nov 4, 1986.

LIST OF WORKSHOP PARTICIPANTS

WORKSHOP COMMITTEE

D.DeBra	Stanford	B.D.McDaniel	Cornell
V.F.Fitch	Princeton	A.Sessler	Berkeley
R.L.Garwin	IBM	S.A.Teukolsky	Cornell
J.L.Hall	JILA	A.Tollestrup	NAL

GRAVITY WAVE RESEARCH SCIENTISTS

A.Abramovici	Caltech	N.Comins	Maine(Orono)
A.Cadez	Caltech		
Y.T.Chen	Caltech	P.Michelson	Stanford
R.Drever	Caltech		
R.Spero	Caltech	A.Brillet	Orsay
K.Thorne	Caltech	P.Tourrenc	Paris
S.Smith	Caltech		
M.Zucker	Caltech	P.Bender	Colorado
G.Leuchs	Max Planck	N.Christiansen	MIT
A.Rudiger	Max Planck	J.Livas	MIT
R.Schilling	Max Planck	M.Burka	MIT
		A.Jeffries	MIT
J.Hough	Glasgow	P.Linsay	MIT
B.Meers	Glasgow	P.Saulson	MIT
B.Schutz	Cardiff	R.Weiss	MIT
H.Ward	Glasgow		

LARGE BASELINE PLANNING AND ENGINEERING

I.Corbett	Rutherford Appleton
R.Elder	JPL
J.Klen	NAL
V.Lobb	JPL
F.Schutz	Caltech/MIT

EXPERTS IN LASERS AND OPTICAL TECHNOLOGY

H.Bennett	Michelson Lab	T.Johnston	Coherent Inc
R.Byer	Stanford	H.Kogelnik	Bell Labs
S.Ezekiel	MIT	P.Silvergiate	Perkin Elmer
C.Volk	Litton	J.Hannon	Kodak
Kotik Lee	Perkin Elmer	•A.Szoke	Livermore
L.Hackel	Livermore	A.Slomba	Perkin Elmer

OBSERVERS

A.Komar	NSF	•F.Allario	NASA Langley
R.Isaacson	Illinois/NSF	M.K.Wilson	NSF
H.Willard	NSF		

•did not attend

NATIONAL SCIENCE FOUNDATION
WASHINGTON D C 20550

October 17, 1986

Dr. Andrew Sessler
Lawrence Berkeley Laboratories
1 Cyclotron Blvd.
Berkeley, California 94720

Dear Dr. Sessler:

Thank you for agreeing to participate as a member of the "Workshop on Gravitational Wave Physics and Astronomy" to be held in Cambridge Massachusetts during the week of November 10. I hope that you will find this a stimulating and interesting five days.

The National Science Foundation is the primary source of Federal support for gravitational physics. The annual budget in this field has grown from $1M per year in 1970 to $8M per year in 1986. The field is currently at the threshold of a major new initiative to develop apparatus and facilities which are projected to be able to detect gravitational radiation from astrophysical sources within the next decade. The estimated cost of this project is approximately $60M in current dollars. The project has been endorsed by the Advisory Committee for Physics of the NSF as a new initiative in the current five year plan and, furthermore, has been given the highest priority by the Panel on Gravitation, Cosmology and Cosmic-Ray Physics of the Physics Survey Committee (Brinkman Committee).

In this period of tightly-constrained budgets, the NSF is in need of your expertise to provide further independent advice concerning this new initiative. More specifically, to be of greatest value for our planning, we request that the workshop:

1) evaluate the scientific case for the development of large facilities to detect gravitational radiation from astrophysical sources,

2) evaluate the probability of detection of gravitational wave signals as a function of gravitational wave receiver sensitivity,

3) review the sensitivity of gravitational wave receivers using current technology, and evaluate the prospects for improved sensitivity,

4) evaluate the vacuum system and construction strategy for the Laser Interferometer Gravitational wave Observatory (LIGO), a joint project proposed by the California Institute of Technology and the Massachusetts Institute of Technology, and

5) evaluate the scientific and technical management plan for the LIGO project.

It would be of considerable help to us if the conclusions of your deliberations of these matters were provided in the form of short reports, with appendices on technical issues should these be required. To be of use in current fiscal planning it would be important to have such documents in hand by mid-December.

Professor Rainer Weiss of MIT has been asked to coordinate the workshop. Details of the workshop program, travel and lodging arrangements will be sent to you from his office.

Let me once again express my appreciation for your generous contribution of time and effort.

Sincerely yours,

Arthur Komar

Arthur B. Komar
Program Director for
Gravitational Physics

Copy to:
Dr. Rainer Weiss
Department of Physics
Massachusetts Institute
of Technology
Cambridge, Massachusetts. 02139

cc: Dr. Harvey B. Willard, DD/PHY
Grant PHY-8504836 A01, MIT (Weiss)
Grant PHY-8504136 A01, Cal. Tech (Drever)

(amended Nov 15,1986) to reflect changes

November 8,1986

Appendix C

WORKSHOP ON GRAVITATIONAL WAVE PHYSICS AND ASTRONOMY

AGENDA

MONDAY NOVEMBER 10

8:30AM	Continental breakfast in Hearth area	
	MEETING IN LARGE CONFERENCE ROOM	
9:00	Welcome	A.Komar, R.Drever, R.Weiss
9:10	Sources of Gravitational Waves and the Scientific Case for the LIGO Project	K.Thorne, B.Schutz
9:50	Discussion	
10:05	Acoustic Receivers	P.Michelson
10:30	Discussion	
10:40	Coffee	
10:55	Introduction to Michelson receivers. General description of noise sources in interferometric receivers	R.Weiss
11:20	Introduction to Fabry-Perot receivers, recycling and resonating techniques	R.Drever
11:45	Discussion	
12:00	Lunch	
AFTERNOON	MEETING IN LARGE CONFERENCE ROOM	
1:00PM	Caltech prototype research	R.Spero and others
1:50	Discussion	
2:00	MIT prototype research	J.Livas, M.Burka
2:50	Discussion	
3:00	MPI/Garching prototype research	R.Schilling, A.Rudiger
3:20	Discussion	
3:30	Coffee	
3:40	Glasgow prototype research	J.Hough and others
4:00	Discussion	
4:10	Paris/Orsay research program	A.Brillet
4:30	Discussion	
4:40	Space based receivers	P.Bender
5:10	Brief comment on 3K background and gravitational wave limits	R.Weiss
5:15	Discussion	
5:30	Adjourn	

8:30AM	Continental breakfast in Hearth area	
	MEETING IN LARGE CONFERENCE ROOM	
9:00	Brief scientific and political history of the LIGO project	K.Thorne
9:20	Discussion	
9:30	Designs for long baseline Michelson receivers to meet initial sensitivity goals	R.Weiss
9.55	Discussion	
10:00	Designs for long baseline Fabry-Perot receivers to meet initial sensitivity goals	R.Drever
10:25	Discussion	
10:30	Coffee	
10:40	Plans to meet enhanced sensitivity and frequency goals. Future uses of the LIGO facilities	R.Drever
11:00	Discussion	
11:10	Seismic isolation and suspension systems for the large baseline system	Caltech/MIT scientists
11:30	Discussion	
11:40	Higher power sources and optical techniques for the large baseline system	Caltech/MIT scientists
12:00	Discussion	
12:10	Lunch	
AFTERNOON	MEETING IN LARGE CONFERENCE ROOM	
1:10PM	Data analysis and storage	P.Linsay, B.Schutz
1:50	Discussion	
2:00	Overview of the presentations to be made on the LIGO project	F.Schutz
2:05	Essential features of the LIGO	R.Weiss, R.Drever
2:25	Discussion	
2:40	Conceptual design and functional requirements of the LIGO	P.Saulson, R.Spero
3:10	Discussion	
3:20	Coffee	
3:30	Sites and site studies	F.Schutz
3:50	Discussion	
4:00	Technical management	F.Schutz
4:15	Detailed engineering design study:plan,schedules,costs Prototype development:lasers,mirrors,vacuum components Projected construction: plan,schedules,estimated costs	F.Schutz
4:50	Discussion	
5:00	Scientific management	K.Thorne
5:15	Discussion	
5:30	Adjourn	

WEDNESDAY NOV 12

MORNING FREE EXCEPT FOR WORKSHOP COMMITTEE, LIGO STEERING COMMITTEE AND NSF OBSERVERS

8:30AM	Continental breakfast in Hearth area	
	MEETING IN SMALL CONFERENCE ROOM	
9:00	Committee deliberation	
10:30	Coffee	
12:00	Lunch for committee and observers	
AFTERNOON	MEETING IN AUDITORIUM OR GARDEN ROOM DEPENDING ON ATTENDANCE	
1:00PM	Squeezed state interferometers	G.Leuchs
1:15	Discussion	
1:20	German plans for a long baseline system	G.Leuchs, A.Rudiger, R.Schilling
1:50	Discussion	
2:00	British plans for a long baseline system	I.Corbett
2:30	Discussion	
2:40	French plans for a long baseline system	P.Tourrenc, A.Brillet
3:10	Discussion	
3:20	Break (no coffee due to other activities at academy)	
3:35	Discussion of effective means of international collaboration	
4:00	Committee questions and general discussion	
5:00	Adjourn (academy is committed after this time)	

THURSDAY NOVEMBER 13

8:30AM	Continental breakfast in Hearth area	

MEETING IN LECTURE HALL

ROUNDTABLE ON OPTICAL TECHNOLOGY FOR GRAVITATIONAL WAVE RESEARCH
PRESENT STATUS AND PROSPECTS

9:00	Introduction	R.Weiss MIT R.Drever Caltech
	LASERS	
9:05	Argon and Nd:Yag laser systems	T.Johnston Coherent,Inc
9:20	Nd:Yag systems	R.Byer Stanford
9:35	High power laser diode sources (talk given by Kotik Lee)	C.Roychaudhuri Perkin Elmer,Inc
9:50	High power laser research at Livermore	L.Hackel Livermore
10:05	Discussion	
10:30	Coffee	
	MIRRORS AND COATINGS	
10:40	Capabilities for grinding,testing and coating mirrors (talk given by A.Slomba)	B.Rigby Perkin Elmer,Inc
10:50	Capabilities for grinding,testing and coating mirrors	J.Hannon Kodak Inc
11:00	Superpolish and low loss coating	C.Volk Litton,Inc
11:15	Mirror figure,scattering and testing	H.Bennett China Lake
11:30	Discussion	
	ELECTROOPTICS,NON LINEAR OPTICS AND FIBERS	
11:45	Electrooptics,non linear optics and fibers	H.Kogelnik Bell Labs
12:05	Discussion	
12:20	Lunch	
AFTERNOON	COMMITTEE MEETING IN SMALL CONFERENCE ROOM GARDEN ROOM OPEN FOR PARTICIPANTS	
1:20PM	Committee deliberations	
3:30	Coffee	
5:30	Adjourn	

FRIDAY NOV 14

MORNING	COMMITTEE MEETING IN SMALL CONFERENCE ROOM
8:30 AM	Continental breakfast in Hearth Area
9:00	Committee deliberation
10:30	Coffee
12:00	Lunch
3:00PM	Adjourn