Technology Development for Third Generation Ground-based Gravitational Wave Detectors

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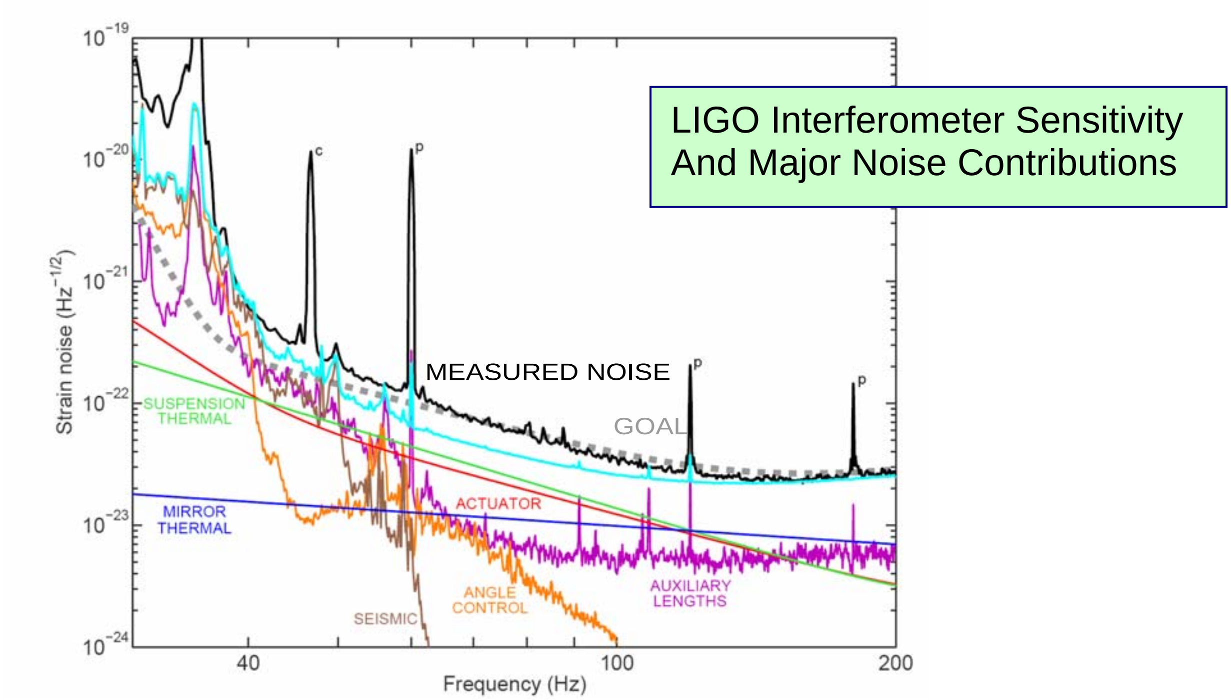
Abstract

Gravitational wave astrophysics is on the threshold of a first direct detection and in the next few years will begin contributing to astronomy. The groundwork for this advance was laid over the past three decades through a vigorous program of R&D. Significant further advances in sensitivity and frequency coverage for third-generation ground-based interferometers are possible and will address questions of major scientific importance. To accomplish this, a forward-looking program of instrumental research should be supported.



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The next decade will see the beginning of gravitational wave astrophysics, as a world-wide network of advanced gravitational wave interferometers already under construction or in the advanced planning stage begin to operate, with a substantial increase in sensitivity and bandwidth over the first generation detectors. These advanced detectors were made possible by a program of R&D that began even before the initial detectors began operation. These advanced detectors do not fully exploit the potential for sensitivity and bandwidth—a third generation of ground-based interferometer detectors seems possible with a factor of 10 increase in sensitivity as well as another decade of lower frequency coverage. We urge support for a broad-based effort to explore and master the techniques required to make this leap. The challenges of gravitational wave detection are formidable, but the reward is an entirely new window with which to explore the universe.

Background—the Current State of Gravitational Wave Detection

Today's most sensitive gravitational wave detectors are Michelson interferometers operating over multi-kilometer baselines between suspended and vibration-isolated mirrors which act as proof masses to sense the spatial strain caused by the gravitational wave.

The largest of these efforts is the Laser Interferometer Gravitational-wave Observatory (LIGO), located in the US [1, 2]. LIGO comprises two 4 km long L-shaped facilities, in Washington and Louisiana. In 2005, the LIGO detectors reached their design sensitivities, capable, for example, of detecting the inspiral and merger of a binary neutron star system out to the distance of the Virgo cluster of galaxies (depending upon orientation). The cover figure shows the strain sensitivity of a LIGO detector compared with its design goal, and shows the numerous contributors to the total noise.

LIGO operates in a network with detectors around the world, including

- GEO600, an interferometer with 600 m arms located near Hannover, built by a German-British collaboration [1,3],
- Virgo [4], a single 3 km interferometer at a facility near Cascina, Italy, operated by a second European collaboration, and
- TAMA, a 300 m long detector [5] located at the National Astronomical Observatory of Japan (NAOJ).

The successes of the various interferometric detector projects around the world have set the stage for an ambitious program of second generation detectors, currently either under construction (Advanced LIGO [6] in the US and GEO HF [7] in Europe) or in advanced stages of planning (Advanced Virgo [8] in Europe, and LCGT [9] in Japan). In their most sensitive regions, these advanced detectors will have a ten times larger range to detect sources than the initial detectors, which translates into a factor of one thousand larger observable volume. The extension of the sensitive frequency band to lower frequencies also greatly broadens the types of sources which may be detected. The operation of these advanced detectors will move the field from gravitational wave detection to gravitational wave astrophysics.

When it is launched, the Laser Interferometer Space Antenna (LISA) [10] will complement the observations of second generation ground-based interferometers with a sensitivity band from 10^{-4} to 1 Hz. LISA is a joint ESA–NASA project and will consist of three spacecraft orbiting the Sun in a triangular formation. Moving the detector to space opens up a rich region of the gravitational wave spectrum below 1 Hz, potentially as different from the high frequency sources as the early radio astronomy sources were from the optical ones.

The Einstein Telescope (ET) Project [11] is supported by the European Commission for the study and the conceptual design of a future European third generation gravitational wave detector. ET shares the science goals discussed below, and close collaboration on the research and planning for any future detectors is planned.

Science Opportunities Opened by Third Generation Ground-based Detectors

Gravitational radiation carries an uncorrupted signature of the nature of the space-time geometry and therefore provides an invaluable tool to observe and understand the behavior of matter and geometry under extreme conditions of density, temperature, magnetic fields and relativistic motion [12]. The higher sensitivity and lower frequency capabilities of third generation detectors would expose new scientific targets.

Fundamental Physics: According to Einstein's gravity the space-time in the vicinity of a black hole is described by a unique geometry called the Kerr solution. The lower frequency capability of third generation interferometers will permit the observation of the radiation from the in-fall of a small black hole into an intermediate mass black hole, making it possible to test such uniqueness theorems. X-ray astronomy has provided firm but indirect evidence that intense sources of x-rays may host black holes. An unambiguous signature of black holes, however, could eventually be provided by the detection of black-hole quasi-normal modes – gravitational radiation that has characteristic frequency and decay time. Failure to detect such radiation from, for example, a newly formed black hole would mean that gravity is more exotic than what we currently believe (e.g., gravitational collapse might lead to entities called naked singularities) or reveal new phases of matter at extremely high densities.

Relativistic Astrophysics: Gravitational wave observations will help elucidate the fundamental nature of a variety of energetic astrophysical phenomena. Examples include the gravitational collapse of a massive stellar core that drives a supernova, the sources of gamma-ray bursts – intense sources of gamma radiation that last only fraction of a second to a minute yet emit more energy than would a star in its entire lifetime, the structure of neutron stars and the state of matter at nuclear and greater density, and magnetars (neutron stars with magnetic fields as high as 10^{15} gauss). In each of these cases, the source is believed to be couched in dense environs and strong gravitational fields and, therefore, a potential source of gravitational radiation. For example, gamma-ray bursts could come from colliding neutron stars which are electromagnetically invisible for most of their lives but are powerful emitters of gravitational waves. Transient radio sources could be the result of quakes in neutron stars with concomitant emission of gravitational radiation. Observing such 'multi-messengers' (sources that are strong emitters of EM, neutrino, and GW radiation) will help understand phenomena that have remained puzzles for decades.

The nucleus of every galaxy is believed to host a supermassive black hole. How do super-massive black holes form? Do they form from small 100 solar mass seeds and then grow by accreting gas and other compact objects? These are some of the questions which a model of the formation of structure in the Universe must answer. While electromagnetic observations have provided all the data so far, gravitational wave observations can help address some of the key questions about the formation and nature of these objects.

Future gravitational wave detectors will be sensitive to sources at high red-shifts. Populations of different sources at such distances will help us understand their cosmological evolution, the history of star formation and their dependence on the matter content of the Universe, the development of large scale structure in the Universe and the formation of the network of super-clusters, the rich environs of galactic nuclei, etc.

Cosmology: The most amazing aspect of the Universe is that only about 3-4 percent of its content is in the form of visible matter, the rest being classified as dark matter and dark energy. In order to clarify the nature of these dark contents it is necessary to understand the scale and expansion of the Universe. Compact binaries are an astronomer's ideal standard candle. By measuring the signature of the gravitational radiation they emit, it is possible to infer their intrinsic parameters (such as the masses and spins of the component objects) and accurately deduce their luminosity distance. Compact binaries eliminate the need to build a cosmic distance ladder and are therefore free from possible systematic effects. Third generation interferometers will detect several hundred compact binary coalescences each year in coincidence with short-hard gamma-ray bursts, provided, of course, the two are related. While gravitational observations would provide an unambiguous measure of the luminosity distance, the host galaxy of the GRB could be used to measure the red-shift. By fitting the observations to a cosmological model, it will be possible to measure the Hubble parameter, dark matter and dark energy densities, as well as the dark energy equation-of-state parameter w, to several percent.

The cosmic microwave background is relic radiation from the big bang, but because the early Universe was so dense this radiation was in thermal equilibrium with matter for about 380,000 years after the birth of the Universe. The most direct way of observing the primeval Universe is via gravitational waves. Theoretical models based on fairly general assumptions predict the production of gravitational waves in the early Universe which have been traveling to us unscathed as a consequence of their weak coupling to matter and other forms of radiation. The absence of foreground interfering sources makes the region between 0.1 Hz and a few Hz one of the most promising windows for looking for a primordial background. The early history of the Universe must have witnessed several phase transitions as the energy scale changed from that of Grand Unification Theory (GUT) to Electro-Weak interaction and finally to the current state in which we see four different fundamental interactions. Cosmic strings are one-dimensional topological defects that form at the boundaries of different phases of the Universe. Vibrations of these strings at the speed of light can sometime form a cusp emitting a burst of gravitational radiation, which may be observed as individual events or as a stochastic background from many overlapping sources. The spectrum of the radiation has again a unique signature which can help us detect cosmic strings and thus provide a glimpse of the Universe as it underwent phase transitions.

Research and Development Directions

The sensitivity of Advanced LIGO (typical of the Advanced detectors) will be limited by two fundamental noise sources: quantum noise (manifest as shot noise at high frequencies and as radiation pressure noise at low frequencies), and thermal noise (due to coatings, substrates and suspensions). Gravitational gradient noise (gravitational forces due to changing mass concentrations in the vicinity of the mirrors), while not limiting yet, is expected to lie just below Advanced LIGO sensitivity at low frequency.

To improve sensitivity and extend the frequency range to 1 Hz or below, a broad program of technology development needs to be pursued, and success on a number of fronts is required. The noise level in an interferometer gravitational wave detector involves many interconnected factors. The following topics are representative of the most fruitful areas of research, but certainly not complete.

Quantum Noise
The most promising method for making improvements in sensitivity at high frequencies is through the injection of squeezed vacuum into the output port of the interferometer. Squeezed vacuum obtained through optical parametric processes in nonlinear crystals has shown suppression of noise, and good performance down to frequencies as low as 10 Hz [13]. Tests of squeezed vacuum injection on suspended interferometers, continued investigations of robust operation, and control schemes appropriate to large interferometers must be pursued. High reliability is required, without a significant increase in the complexity of operation of the instrument. This will set certain restrictions on manufacturing approaches and materials selection especially for the nonlinear materials. There is additional work to improve the method of injecting the light into the interferometer, to reduce the insertion loss of components such as Faraday isolators and output mode cleaners, and to improve the quantum efficiency of photodiodes.

At low frequencies, radiation-pressure forces in conventional interferometers combine with shot noise to produce the so-called Standard Quantum Limit, the macroscopic manifestation of the Heisenberg Uncertainty Principle. However, the uncertainty principle that limits conventional techniques does not set a hard limit to sensitivity. Injection of squeezed vacuum can be used in this regime, but the phase of the squeezing has to be rotated as a function of frequency [14]—this has never been demonstrated nor have appropriate control schemes been designed. Alternatively, a strong optical spring can be set up allowing the (lower) quantum noise of a two-mirror harmonic oscillator to take over from the free mass one [15]. These springs can also reduce the coupling of classical force noises (such as thermal noise) to the mirror. Such interferometers operate in the largely unexplored regime where radiation pressure forces dominate the mirror dynamics.

Improvement can also be gained, in principle, by removing radiation pressure effects using non-conventional techniques. Studies of alternative interferometer topologies have shown that there should be configurations that can meet this goal: namely, "optical-bar" and "optical-lever" techniques [16].

Thermal Noise

Thermal noise manifests itself in numerous places: suspensions, the internal degrees of freedom in the mirrors, and mirror coatings [17]. Each source of thermal noise must be addressed and overcome. Thermal noise can be reduced by operation at cryogenic temperature (see next topic), but the gain is only proportional to $T^{1/2}$. The largest gains are likely to come from reduced mechanical losses.

Low thermal noise suspensions are crucial for extending the low frequency performance. Silicon has attractive thermal and thermo-mechanical properties making it a strong candidate for the suspension elements in future detectors, including those operating at cryogenic temperatures, to reduce thermal noise. It is also conductive which may have advantages for controlling charging effects. The development and measurement of suitable suspension flexure elements, including studies of the optimum material, its thermal noise properties, and the geometry and assembly of elements including methods of bonding to test masses must be pursued. Development of silicon blade springs for improved vertical isolation and thermal noise lower than that obtained with current maraging steel blades is an attractive option. Considerations of how to suspend large (100 kg or more) masses, possibly at cryogenic temperatures, are also important. Particular challenges of a suspension system for such masses include maintaining low suspension thermal noise and high seismic and mechanical isolation, incorporating actuation, and integrating such a system into a detector. Optical fabrication of such large masses will also be an issue.

Alternative substrate materials may give reduced internal thermal noise, especially for use in low temperature detectors [18]. Both silicon and sapphire potentially offer superior performance at cryogenic temperatures and/or at particular frequency bands. For silicon, efforts will focus on fabricating large cylindrical test specimens and investigating their mechanical properties as a function of doping. Preliminary experiments measuring the dissipation have been carried out and reveal disagreement with theoretically predicted loss. Preliminary efforts with sapphire have yielded information about its mechanical and optical properties, methods for growing and processing large blanks, and ways to achieve high homogeneity and low absorption. Data at low temperature are important to predict the performance of cryogenic sapphire test masses.

Mirror thermal noise will be one of the fundamental factors limiting the sensitivity of Advanced gravitational wave detectors [19]. Identifying the root cause(s) of mechanical dissipation in coatings is a crucial step in developing improved techniques for reducing coating loss, which could be of considerable interest for allowing enhanced performance for third generation detectors. Alternative materials, proper annealing treatments, and optimized coating designs may lead to reduced coating losses. Cryogenic experiments can yield significant information about the dissipation mechanisms in coatings, through their behavior as a function of temperature. A thorough understanding of thermophysical, mechanical and optical properties of mirror materials at low temperatures will be needed.

A complementary approach involves the use of larger beam profiles to average over thermal fluctuations across the mirror surface. Non-spherical mirrors, shaped to support flat intensity 'mesa' profile beams, have been designed and fabricated using specialized coating techniques [20]. Preliminary tests have been made to demonstrate the use of such mirrors in locked cavities. Further studies need to address alignment correction signals via wavefront sensing, angular instabilities at high power and thermal distortions.

There are also ideas of circumventing coating thermal noise using corner reflectors or short Fabry-Perot cavities as end mirrors [21]. Corner reflectors would allow for no coatings to be used and the cavities would allow for much thinner coatings than conventional mirrors. Developing these ideas so they can be used in an operating interferometer will require a series of demonstration experiments at increasing scales.

Cryogenics

Cryogenic operation introduces a number of complications for precision interferometers, but the benefits are obvious, in the reduction of thermal noise, and subtle, in the case of improved material properties at low temperatures (as described above). The Japanese Project LCGT is investigating the use of cryogenics in gravitational wave interferometers.

A major challenge is to provide an efficient path for heat conduction while still maintaining good thermal noise and mechanical isolation performance [22]. The cooling system needs to provide adequate heat extraction from the cooled test masses, for both steady state operation and for cooling from room temperature in a reasonable time, without adding noise or short-circuiting the mechanical isolation. High frequency interferometers, for which shot noise is a critical factor, may use circulating powers in the range 1 MW, and even with anticipated coating absorption of 0.5-1 ppm, the absorbed power is 0.5 to 1 W per optic. Conductive coupling through suspension fibers needs to be evaluated.

Other novel methods of heat removal to be explored include radiative coupling between two objects: one hot and one cold. Simple radiative cooling to a surrounding cold environment can provide cooling if the heat input is sufficiently low, as might be the case in an interferometer optimized for low frequency operation. An alternative is to attempt to couple to evanescent fields outside the hot object. If a cold object with appropriate properties is introduced into this evanescent field region, energy is transferred, cooling the hot object. The heat transfer can be greatly enhanced using a small gap but this is accompanied by force coupling that needs to be taken into account.

Finally, a potential downside of cryogenic mirrors is the risk of contamination. Methods will need to be developed to (i) mitigate the level of contamination in cryogenic mirrors, (ii) quantify the magnitude and type of contaminants, and (iii) if necessary, clean contaminated mirrors *in situ*.

Gravitational Gradient Noise
Vibrations of the ground and density fluctuations of the air produce fluctuating Newtonian gravitational forces on interferometer optics [23]. Although we can reduce the direct vibrational coupling via improved seismic isolation, there is no way to shield the test mass from gravitational forces. Current estimates predict that the motions of the test mass resulting from this Newtonian noise will become a limiting noise source somewhere between 10 and 20 Hz [24]. On the earth's surface, the dominant contribution is due to vertical seismic motion as dense soil replaces air. Forces from atmospheric density fluctuations are predicted to be smaller, but not negligible. There are a number of techniques under consideration to address this. These include putting the detectors underground, and/or measuring the local ground disturbances with an array of sensors, and developing a computer model which allows us to predict the gravitational coupling of the environment to the test mass.

It may be possible to suppress the seismic noise contribution by using a two-dimensional array of seismometers around the interferometer to track the motion of the ground and subtract its gravitational coupling from the mirror motion. By 'training' the model with data from the array and the detector, it may be possible to subtract a large fraction of the Newtonian noise from the gravitational wave signal channel in real-time or in post-processing. The atmospheric contribution includes pressure and temperature fluctuations, wind, rain etc., and it is not clear whether it is feasible to design an active system to track the atmospheric conditions and suppress this noise source. Finally, human factors, including effects such as ground and air traffic, could be even more difficult to remove.

Developing an underground GW detector would be beneficial for all three sources of gravity gradient noise. Atmospheric fluctuations and human-induced gravitational fluctuations are more distant and controllable underground. This leaves the seismic ground motion as the dominant source of gravity gradient noise underground. However, even this source is expected to be significantly reduced underground. Seismic noise itself decreases with depth. Preliminary measurements at a depth of 2000 feet at the Homestake mine (proposed as the site for DUSEL) indicate a factor of 10 lower seismic noise at 1 Hz [25], comparable to the quietest measurements anywhere on the earth's surface. The speed of sound underground is around 5 km/s, implying that the seismic waves in the 0.1-10 Hz band have very large wavelength: 500 m - 50 km. This is much larger than the size of a cavity that would host one of the interferometer mirrors, so to zeroth order the passage of seismic waves would have little effect on the gravitational field at the center of the cavity. It is currently unclear how large is the effect of various imperfections in realistic settings. This includes rock density non-uniformity, anisotropy in the sound velocity, boundary conditions and so on. It is therefore crucial to measure the seismic noise underground in great detail, substantially better than what has been done in the past. The Homestake mine offers an excellent opportunity for a detailed set of measurements of the seismic motion.

Other directions
The design of the Advanced LIGO interferometers allows for tuning of the frequency response by changing the signal cavity length (microscopically) and by changing the optical spring frequency (by adjusting the circulating laser power). By replacing the signal

recycling mirror with a resonant cavity the bandwidth and peak frequency of the interferometer's response curve can be tuned to tailor the sensitivity to match particular astrophysical sources. Further research to develop control schemes capable of implementing these schemes, including possible dynamic tuning, should be explored.

All-reflective interferometers using diffraction gratings as optics avoid problems associated with the transmission of large laser powers through optical substrates [26]. High finesse optical cavities have already been demonstrated using small area gratings. The challenge will be to scale up the optical aperture to what is required for a large scale detector. In addition, absorption by the grating surface will distort its surface profile, possibly resulting in changes in the beam profile as well as power-dependent changes in the diffraction angle and efficiency. Although some modeling has been done, these effects have yet to be seriously investigated. Investigations of mechanical loss in gratings are needed to verify thermal noise levels.

Program Scope

The proposed program would be carried out broadly by the LIGO Scientific Collaboration (LSC), the LIGO Laboratory, other international gravitational wave groups (most notably the Einstein Telescope project described above) and other interested investigators not currently engaged in gravitational wave research but who will bring particular skills and resources to the undertaking. The LSC (of which the LIGO Lab is a member), provides a means to coordinate R&D activities to avoid unnecessary repetition and to communicate between different research areas to ensure that systems aspects of the R&D program are properly taken into account. International collaboration is facilitated by direct agreements for collaborative activities, and by periodic workshops to share new ideas and developments.

Because the actual course of the research will evolve as new results are obtained, it is difficult to estimate the appropriate scope. In 2004, gravitational wave astronomers and astronomers from more traditional disciplines met at Penn State for a workshop entitled “Imagining the Future: Gravitational Wave Astronomy.” The purpose of the workshop was to initiate discussions on a variety of topics aimed at drawing gravitational waves into the broader astronomy community. One of the major conclusions at this meeting was that the future evolution of the field needed to have a suitable level of forward-looking R&D; a level of 5-10% of the total investment in the field was judged to be the appropriate level for this effort [27], based largely on the experience in other technology intensive endeavors. At the current levels of support for LIGO activities in the US, this would mean an investment of $2-4 M per year in the U.S., with comparable efforts in other parts of the world funded through their normal channels.

The timing for the proposed work should support the design and evaluation of third generation detectors in the era beginning shortly after the initial operation of the Advanced detectors, near the middle of the next decade. Many of these R&D activities will require concentrated, extended efforts, and an early start. The goal is to have sufficient results to design and plan third generation interferometers to be ready for consideration in the next decadal survey.

Synergies with other fields

Gravitational wave research has always been an “instrument technology intensive” field, pushing the frontiers forward at once in many fields. The proposed technology development program is certain to impact fields outside of astronomy and astrophysics:

Macroscopic quantum mechanics: Early gravitational wave research was the motivation for a number of fundamental concepts in the confrontation between quantum mechanics and macroscopic objects: Quantum Non-Demolition measurements, the Standard Quantum Limit and Back-Action Evasion. More recently, optical rigidity and damping/anti-damping have been used extensively in experiments involving mechanical oscillators, with the aim of reaching a Heisenberg-Limited mechanical quantum state.

Lasers: The development of cw high power single frequency 1064 nm lasers has been driven by the gravitational wave field and these devices have seen a number of applications. The RF reflection locking technique for lasers (Pound-Drever-Hall) developed for gravitational wave detectors has become a standard stabilization method for obtaining low line widths for spectroscopic and frequency standards applications. Future developments, including fiber lasers, may similarly find wide application.

Optics: The development of large optics (25-35 cm diameter) with surface figures approaching $\lambda/1000$ has been significant for precision metrology, x-ray optics, and other optics applications.

Optical testing: The devices developed to characterize these high precision optics and coatings have found application in the semiconductor fabrication world. Recently developed high performance Hartmann sensors ($<\lambda/10000$) may be used in optometry and optical diagnostics for both technology and science.

Coating development: Research on mirror coatings by the gravitational wave community has led to the conclusion that thermal noise in coatings is a major limitation to the performance of state of the art frequency standards, and continued development of low noise coatings will serve this community as well.

Geophysics: Characterization of underground experimental sites, in high stability hard rock environments, presents a good opportunity for geophysical measurements. The temperature stability and low seismic noise are commonly beneficial to both geophysics and gravitational wave detection.

Cryogenics: Cryogenic systems with vibration isolation within a cryogenic environment are of direct relevance in the field of optical frequency standards where lasers are stabilized to cryogenic cavities which have to be undisturbed by mechanical noise.

Summary

Gravitational wave astrophysics is on the threshold of a first detection and in the next few years will begin contributing to astronomy. The groundwork for this advance was laid over the past three decades through a vigorous program of R&D. Significant further advances in sensitivity and frequency coverage for third-generation ground-based interferometers are possible and will address questions of major importance. To accomplish this, a vital and forward-looking program of instrumental research should be supported.

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