Second Generation Gravitational Wave Detectors

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Second generation gravitational wave detectors are in process of being researched, designed, and constructed. They include Advanced LIGO in the United States, Advanced Virgo in Italy, the Large Cryogenic Gravitational-wave Telescope in Japan, GEO High Frequency in Germany, and the Australian International Gravitational Observatory in Australia. It is expected that these second generation detectors will have the sensitivity needed to regularly detect gravitational waves and usher in the era of gravitational astronomy. To achieve this sensitivity, new technology to reduce seismic, thermal, quantum and other noise sources is being developed and implemented. Advanced LIGO, Advanced Virgo, and GEO HF have already been funded and are building and buying new hardware, while LCGT is awaiting a funding decision, and AIGO is preparing to submit a funding proposal.

Keywords:

1. Introduction

Second generation gravitational wave detectors are being proposed, designed, and built in a number of countries. These instruments are designed to go beyond the first generation by increasing sensitivity, bandwidth, flexibility in frequency response, geographical distribution, and other crucial parameter. These improvements should allow for detection of gravitational waves and the beginning of gravitational astronomy. The particular projects and detectors that will be discussed here are the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO),[1] Advanced Virgo,[2] the Large Cryogenic Gravitational-wave Telescope (LCGT),[3] GEO High Frequency (GEO HF),[4] and the Australian International Gravitational Observatory (AIGO).[5]

Advanced LIGO is the name for the successor project to initial LIGO[6] in the United States. Both Advanced LIGO and initial LIGO have three interferometers; two at the Department of Energy reservation in Hanford, Washington and one in Livingston, Louisiana. In Advanced LIGO all three detectors will have 4 km long Fabry-Perot arms, unlike initial LIGO where one of the Hanford detectors had half length 2 km long arms. The vacuum system, support buildings, and some electronics will be carried over from initial LIGO, otherwise all hardware is being upgraded.

Advanced LIGO was funded in 2008 and parts are being fabricated and procured.

Advanced Virgo is an improved detector to be built in the vacuum chamber that houses the initial Virgo interferometer outside of Pisa, Italy. Both initial and Advanced Virgo have 3 km long Fabry Perot cavity arms. Nearly all hardware from initial Virgo, other than seismic isolation, will be replaced in the upgrade to Advanced Virgo. The low frequency seismic wall resulting from superattentuator suspensions in initial Virgo will be maintained in Advanced Virgo, resulting in a low frequency cut off of 10 Hz. Advanced Virgo was funded in late 2009 and is now beginning fabrication and procurement.

The Large Cryogenic Gravitational-wave Telescope is a planed 3 km, cryogenic, underground interferometer to be built in Kamioka, Japan. This is a successor project to TAMA[7] but more ambitious, being longer and incorporating the new technologies needed for cryogenics and underground operation. The proposal for LCGT is under consideration with funding requested for 2010.

The GEO High Frequency (GEO HF) detector is an enhancement of the 600 m long, delay line arm interferometer GEO 600 operating near Hannover Germany. As the name implies, it is focussed on improved sensitivity in the high frequency, $>$ 200 Hz, regime by using squeezed light among other improvements. Many of the second generation technologies planned for use in other projects (multistage pendulum suspensions, silica fibers, signal recycling, etc.) were used successfully in the first generation GEO 600. GEO HF currently has funding for individual subsystem upgrades.

The Australian International Gravitational Observatory (AIGO) is a proposed detector in Western Australia where an 80 m prototype is already in operation. It will have 4 km Fabry cavity arms, and may draw on the designs for Advanced LIGO for many subsystems. The addition of a large scale detector in the southern hemisphere would greatly increase the ability of the world wide network to do gravitational wave astronomy.

2. First Generation Overview

Second generation gravitational wave detectors are designed to build on the first generation experience. The first generation detectors initial LIGO, initial Virgo, TAMA, and GEO 600 reached sensitivities near to their fundamental noise limits and came near to or even exceeded their design goal. A comparison of the design sensitivity of initial Virgo and Advanced Virgo is shown in Figure 1. At low frequencies, first generation detectors demonstrated that the seismic isolation and suspension designs do isolate test masses from ground noise sufficiently to keep it below other fundamental noise in the detection band. Test mass motion from ground noise was also kept to low enough RMS for interferometer lock to be acquired. In the mid-frequency band, technical noise was reduced to roughly the level of the suspension thermal noise from wire loop suspensions, and it approached the expected level of noise from the mirror coatings. At high frequencies, observed noise agreed well with shot noise from the light in Fabry-Perot and power recycling cavities driven by, typically, 10 W lasers.

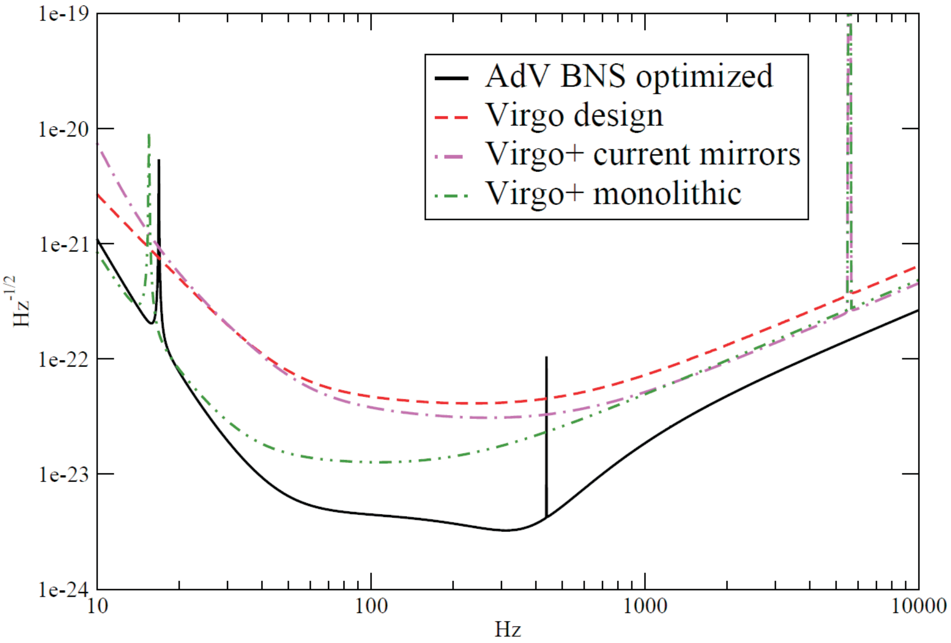

Fig. 1. Design noise of Advanced Virgo compared with initial Virgo and some intermediate upgrades to initial Virgo. "BNS optimized" refers to a signal recycling configuration optimized for binary neutron star inspiral signals.

First generation detectors also demonstrated the feasibility of important technologies that will be crucial to second generation detectors' success. These include the monolithic silica suspensions used in GEO 600, which will be used to reduce thermal noise, superattenuator seismic isolation used in initial VIRGO to get a lower frequency seismic wall, and signal recycling used in GEO 600 to reduce and tune quantum noise. The general principles needed for control of large, 10 kg, scale mirrors to the necessary precision as well as lock acquisition in interferometers with multiple linked cavities were also perfected in first generation instruments. Much of the electronics and software used in first generation detectors will be carried over for use by second generation.

Finally, despite not detecting any gravitational waves, the first generation instruments did provide some interesting astrophysical limits and null results. These are detailed more fully elsewhere,[8] but there are some particular results that will form part of the baseline of expectations for second generation detectors. These include demonstrating that the Crab pulsar is not spinning down due to gravitational wave emission,[9] gamma-ray burst GRB070201 in galaxy M31 was not a neutron star inspiral,[10] and beating the theoretical limit on the level of stochastic gravitational waves coming from Big Bang nucleosynthesis arguments.[11] Further astrophysical results from first generation instruments are still possible, as many are currently running and/or being given incremental improvements in preparation for further operation. But it seems increasingly likely that the first direct, confirmed detection of an astrophysical gravitational wave will come from second generation gravitational wave detectors.

3. Sensitivity Limitations

In order to begin the era of gravitational astronomy, second generation detectors will have to surpass the first generation in a number of ways. A direction and source averaged[12] range to binary neutron star inspirals of 150 to 200 Mpc is a realistic goal for most second generation detectors. With this sensitivity, multiple detections of neutron star, 10 solar mass black hole, and mixed neutron star-black hole binaries per month are expected.[13] This astronomical reach will require roughly an order of magnitude improvement in amplitude (meters/$\sqrt{\mathrm{Hz}}$) noise over the first generation instruments. Wider bandwidth will also be valuable, with a low frequency cutoff around 10 Hz. This will allow for longer observations of low mass objects such as neutron stars plus the ability to detect signals before coalescence of more massive objects (hundreds of solar mass).

Having more multi-kilometer length detectors than there were in the first generation will also augment the astrophysics that can be done. Such detectors should include, in addition to the North American and European similar to first generation, a high sensitivity Asian detector in Japan, and a southern hemisphere detector in Australia. A wider network will improve signal-to-noise ratio, allow for determination of the gravitational wave polarization, provide better localization of events on the sky including potentially identifying host galaxies (see Figure 2), better determination of the speed of gravitational waves, as well as improved uptime and duty cycle.

To meet these goals, the hardware subsystems of second generation gravitational wave detectors will use improved technology. In the following subsections, each major category of limiting noise is explored along with the techniques and hardware planned to reduce this noise to the level needed by second generation interferometers. Some of these plans are definite and hardware is already being constructed, while others are still under consideration. The distinction will be made where appropriate.

3.1. *Seismic Noise*

Seismic noise is any noise that causes the ground (and connected buildings) on which the detector is built to move. This can include earthquakes, ocean waves, tides, changes in groundwater levels, wind, as well as anthropogenic effects like vehicle traffic, people walking, construction, tree harvesting, etc. This noise is typically

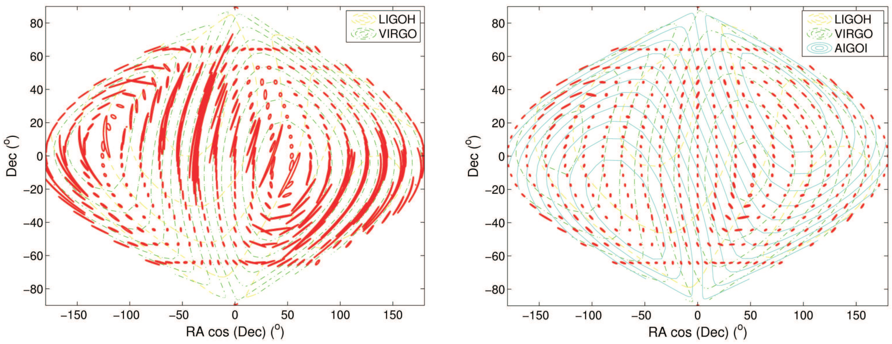

Fig. 2. Localization of gravitational wave events with multiple detectors. The graph on the left shows error ellipses for typical events using the three North American LIGO detectors and Advanced Virgo. The graph on the right shows error ellipses for the same events but includes AIGO.

more pronounced at low frequencies, and is reduced by insulating the test masses and other sensitive optics from the ground with isolation systems. This must be done in all six degrees of freedom, both to reduce the RMS motion to make control and lock acquisition possible, but also because of cross talk between the direction the interferometer senses and other degrees of freedom.

First generation detectors typically used passive mass and spring subsystems which greatly reduced the motion due to seismic disturbances above some normal mode frequencies. Active systems, see Figure 3, still use masses and spring but now sense displacements and/or velocities of parts of the subsystem. These signals are then fedback to actuators which then actively reduce the motion and thereby increase the amount of isolation the subsystem provides. The feedback control system increases the complexity of the subsystem beyond the simple passive stack, and requires additional commissioning. An active seismic isolation subsystem is planned for Advanced LIGO[14] and being considered for AIGO.

A superattenuator,[15] see Figure 4, is a passive mass and spring isolation system, but gets improved performance by having very low ($\sim 0.2 - 0.5$ Hz) normal modes. This is achieved by having multiple pendulum stages which provide horizontal isolation. Each pendulum stage is supported from the one above by cantilever blades with geometric anti-springs on them to provide vertical isolation. The low normal mode frequencies in the horizontal degree of freedom is achieved by having long ($\sim$ 1 m) pendulum wires between stages, and the geometric anti-spring similarly reduces the vertical normal mode frequencies. The whole subsystem is supported from the ground using an inverted pendulum preisolator. Large motions of the test masses at the normal mode frequencies, which would make control and lock acquisition difficult, are reduced using sensing and feedback. These superattenuators were used successfully in the first generation Virgo interferometer and are planned for use in Advanced Virgo and LCGT. Problems with tilt in the initial Virgo inverted pendulums will be reduced by controlling the inverted pendulum in all six degrees of freedom and using tiltmeters as input for that control.

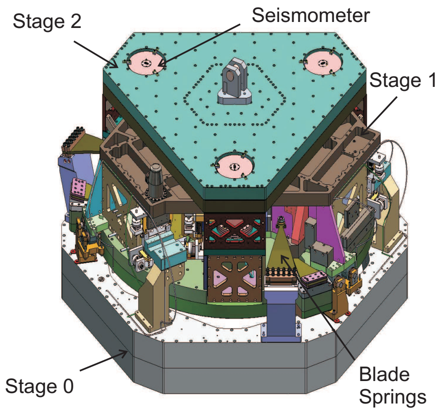

Fig. 3. Advanced LIGO active seismic isolation subsystem. A Stage 0 is supported by support tubes which come in from outside the vacuum chamber. Stage 1 is supported from Stage 0 by steel blade springs, as is Stage 2 from Stage 1. A vertical seismometer in Stage 2, used for feedback, is also shown.

Fig. 4. Superattenuator to be used in Advanced Virgo and LCGT. The three tall grey bars on the outside are the inverted pendulum. Below the top of the inverted pendulum a round stage is supported that contains the blade springs with the geometric anti-springs. There are multiples stages of pendulums supporting blade spring wheels. At the bottom is a control platform that supports the test mass.

Further reduction in seismic noise at the test masses is possible using a suspension point interferometer (SPI). This is an active feedback system that uses additional interferometers to control the separation between different seismic isolation platforms. Thus seismic noise that causes differential motion between two test masses, which is what the primary interferometer is sensitive to, will be reduced. An SPI requires a direct optical path between the seismic isolation platforms of separated test masses. This can be challenging to achieve with first generation vacuum systems which were not designed to be used with SPIs. LCGT is planning on using suspension point interferometers, as its vacuum system is being constructed along with the detector. SPIs are under consideration as possible enhancements in Advanced LIGO and Advanced Virgo, as these detectors are reusing first generation vacuum systems.

3.2. *Gravity Gradient Noise*

Gravity gradient noise occurs from coupling of test masses to nearby ground or other masses through Newtonian gravity. It becomes a noise source at low frequencies if the ground or other surrounding mass (such as the air) moves or changes. So it represents another path for seismic disturbances to cause test mass motion. First generation interferometers were not limited by gravity gradient noise and took no special steps to reduce or avoid this noise source.

One way to improve the environment around a detector and reduce gravity gradient noise is to build the interferometer underground. Having solid ground on all sides of the test mass, as opposed to only below it as happens on the surface, reduces gravity gradient noise by about an order of magnitude. Seismic noise is also typically lower below the surface, reduced by about a factor of 100 after a few hundred meters.

LCGT will be built between 100 and 200 m underground in the Kamioka mine of central Japan. This will result in lower seismic and gravity gradient noise, although there may be challenges involved in keeping the necessary equipment from causing additional seismic disturbances. A prototype interferometer, the Cryogenic Laser Interferometer Observatory, CLIO, is already operating at 1000 m depth in the Kamioka mine, see Figure 5. This will give valuable experience and feedback for LCGT as well as potential third generation detectors, such as the Einstein Telescope,[16] that are considering operating underground.

For second generation detectors that are not going to be sited underground, adaptive filtering is another approach that is under consideration to reduce gravity gradient noise. This technique would use an array of seismometers around the test masses to measure the seismic environment in real time. The data from this array would then be used to feed forward to the test masses so that an actuator could alter their position. This would then cancel out the noise introduced by the gravity gradients. This can be done in an adaptive manner to handle the changing environment around the detector. This technique has been explored in prototype interferometers and is under consideration for use in Advanced LIGO, Advanced Virgo, and AIGO. It could also be combined with underground operation to even further reduce gravity gradient noise in the LCGT. Note that this technique is not restricted to reduction of gravity gradient noise, and might be used for other environmental disturbances.

3.3. *Suspension Thermal Noise*

Thermal noise arising from thermal vibrations in key materials in the detectors is an important noise source in the mid-frequency, 50 to 200 Hz, range. First generation detectors used pendulum suspensions for the test masses and other crucial optics to further isolate them from seismic disturbances. Thermal noise from the suspension material was an important consideration in first generation detectors[17] and much work has gone into making improved suspensions for second generation

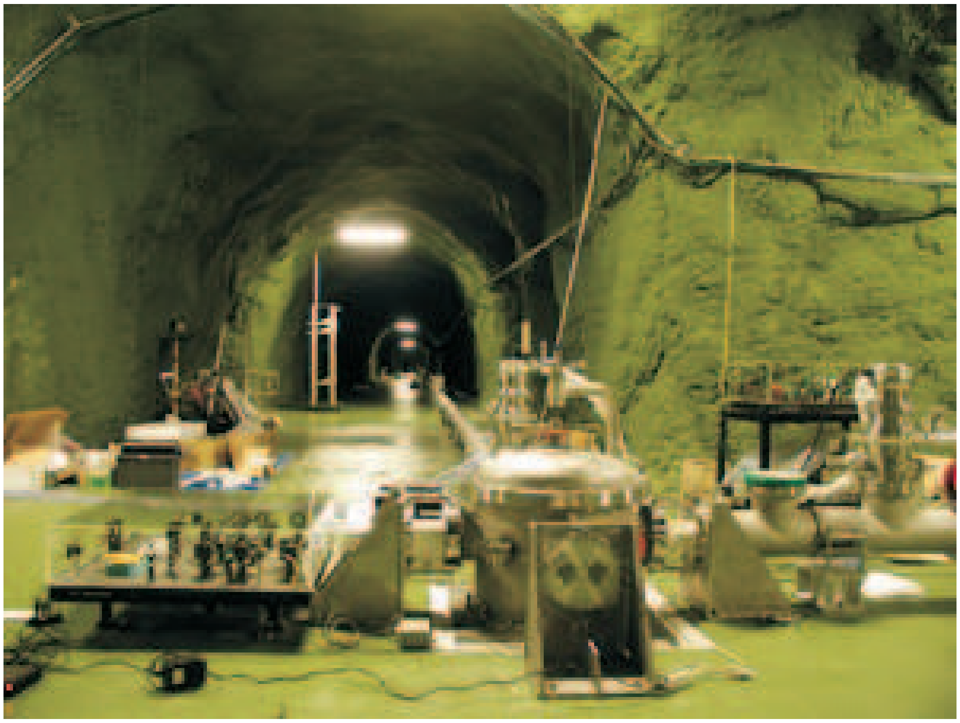

Fig. 5. Photograph of CLIO equipment underground at the Kamioka mine in Japan. Shown are vacuum tubes and input optics for the interferometer.

interferometers. All first generation gravitational wave detectors except for GEO 600 used steel wires for the final pendulum. Steel is strong, readily available, and easily workable. Steel also gives fairly good thermal noise performance for a metal but not good enough to meet the sensitivity goals of the second generation.

GEO 600 uses fused silica fibers for the final stage of the triple pendulums that support its test masses, and fused silica is planned for use in Advanced LIGO, Advanced Virgo, AIGO, and GEO HF. Silica pulled into thin fibers can have very high strength, as long as there is no damage to the surface of the fiber, and can have a mechanical loss, which is directly responsible for thermal noise through the fluctuation-dissipation theorem,[18] as low as 10^{-3} of steel's.

It is important that the connections between the suspension fibers, test mass, and supporting structures are also low mechanical loss so as not to have these connections dominate the thermal noise budget. All second generation detectors with fused silica suspensions will have silica test masses as well as silica masses where the suspensions connect above the test masses. These silica test masses will have silica attachment blocks bonded to them using hydroxy-catalysis bonding.[19] These bonds do have higher mechanical loss than the surrounding silica, but the size and position of the bonds is chosen so that they do not cause excess thermal noise above that caused by the suspension fibers. There is some concern about non-Gaussian noise from these bonds, and research is pursuing that question. The silica fibers are then welded, using either a hydrogen-oxygen torch or a carbon dioxide laser, to the silica attachment blocks. There are some design differences between second generation detectors, notably Advanced LIGO and Advanced Virgo, about when the bond is applied during assembly and whether the bond is in shear or compression while under operation. In any case, this technique makes for a quasi-monolithic suspension of silica in the final pendulum stage of these detectors.

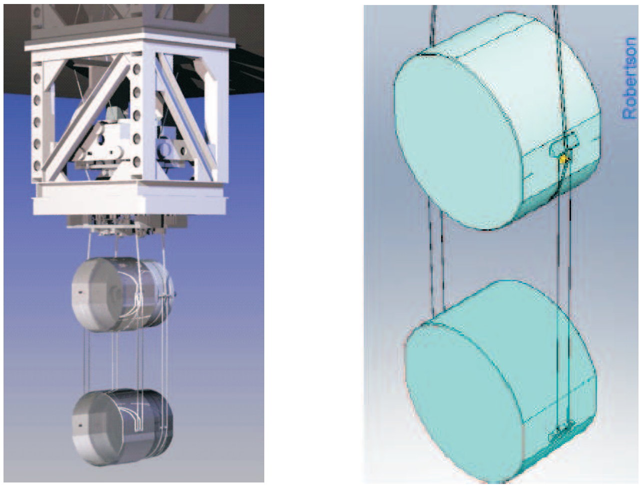

Fig. 6. Model of Advanced LIGO monolithic fused silica suspensions. The drawing on the left shows the test mass at bottom and a penultimate mass above it, both made of silica, connected together with silica fibers. Above the penultimate mass are additional metal masses that complete the quadruple pendulum suspension. Also visible behind the silica masses is the reaction chain, which gives a low noise platform from which control forces can be applied. The drawing on the right shows a close up of the fibers, where two silica fibers on each side of the masses are connected to silica attachment blocks. Standoffs can also be seen on the penultimate mass. These place the metal wire that supports the mass above the silica attachment blocks so there is no interference.

Silica does not have attractive thermal noise properties at low temperatures, as the effect on thermal noise of its mechanical loss increases faster than the effect of temperature decreases. Since LCGT is designed to operate at 15-20 K, it is planning to use sapphire ribbons for the final pendulum stage of its suspension. Sapphire has low mechanical loss at room temperature that improves at lower temperatures. At room temperature, however, it suffers from thermoelastic noise[20] making it unsuitable for use in suspensions. Thermoelastic noise in sapphire is greatly reduced at low temperature, which makes it a very attractive material for the LCGT suspension. The test masses in LCGT will be sapphire as well, so to make a quasi-monolithic suspension a sapphire to sapphire bond must be created between the masses and the suspension ribbons. Hydroxy-catalysis bonding can be used to connect other oxides than silica together and has been shown to work on sapphire.[19] The mechanical loss of the sapphire bonds is not as well studied as the silica bond, and there are similar concerns about non-Gaussian noise.

Another way to improve suspension thermal noise is through geometry. The cross section of the suspension fibers should be made as small as possible consistent with the strength needed to support the test masses. The smaller the dimension in the direction of bending, the less elastic energy is generated with pendulum motion. Since only elastic energy, not the gravitational energy that the test mass acquires with pendulum motion, contributes to thermal noise, this smaller dimension leads to lower noise. This is the motivation for the ribbon geometry, which is planned for the LCGT sapphire suspension, as it allows a larger cross section, which increases strength, but keeps the elastic energy of bending for pendulum motion low. Silica ribbons were considered for Advanced LIGO, but it was found that by a careful design of a fiber profile the noise could be lower than for fibers than for ribbons.[21] Fibers have also proved easier to fabricate efficiently. Similarly, lengthening the final suspension stage reduces noise by lowering the pendulum frequency. This improvement is limited by the violin mode frequencies, as these need to be high for control purposes.

Using these improved materials and geometries, the suspension thermal noise of second generation detectors will typically be at roughly the same level as the radiation pressure from the light. The radiation pressure noise, however, can be adjusted by reducing the laser power or changing the signal recycling configuration. The suspension thermal noise can not be adjusted, so it, along with gravity gradient noise, represents the lower limit of sensitivity in the low frequency band.

3.4. *Mirror Thermal Noise*

Mirror thermal noise, like suspension thermal noise, depends on the materials and the geometry. Mirror thermal noise is usually divided between substrate and coating. First generation detectors were not limited by mirror thermal noise, although they did approach that level. The mirrors were made of fused silica substrates and ion beam deposited silica-tantala coatings, all chosen for their optical properties. In the second generation, thermal noise from mirror substrates will still not be a limiting noise source, but the thermal noise from the optical coatings will then play an important role.

The test mass substrates will continue to be made from fused silica in Advanced LIGO, Advanced Virgo, and GEO HF. Thermal noise from a silica substrate will be well below other noise sources, and silica has excellent optical properties. There is also the advantage of familiarity and the experience that is available from other optical uses. Single crystal sapphire is also planned for use by second generation detectors. The higher Young's modulus of sapphire reduces Brownian thermal noise (but not thermoelastic) from both the substrate and coatings. LCGT is planning to use single crystal sapphire mirrors because of sapphire's low temperature performance. Sapphire is not attractive at room temperature because of high thermoelastic noise, but changes in material properties at cryogenic temperatures make it suitable for LCGT. The high thermal conductivity of sapphire is also desirable when managing the heat deposited by the laser in a cryogenic mirror. AIGO is also considering sapphire mirrors, despite being a room temperature detector. This is motivated by concerns about parametric instability.[22] Thermoelastic noise from sapphire mirrors will likely be a limiting noise source in AIGO. This is in contrast to other second generation interferometers, where substrate thermal noise will be a technical noise source.

Coating thermal noise will be the primary contributor to mirror thermal noise in second generation detectors, and in most cases will be the limiting noise source in the mid frequency band. These middle frequencies (~ 50 to 200 Hz) are typically the band with highest sensitivity. A targeted research program[23] found that the high index tantala in the first generation coating is the primary source of coating thermal noise. Followup research[24] has found that adding titania to tantala reduces mechanical loss, and thus thermal noise, while also reducing optical absorption (important to minimize thermal lensing problems[25]) and keeping other important properties the same. This improved titania doped tantala/silica coating will be used in Advanced LIGO, Advanced Virgo, and AIGO. LCGT will continue to use the first generation tantala/silica coating and rely on lower temperature to reduce the coating thermal noise. GEO HF will stay with the first generation coating as well, as coating thermal noise is not as crucial at the higher frequencies that it is targeting.

Coating thermal noise also depends on the thickness of the coating and the spot size of the laser that reflects off of the mirror.[26] Both of these will be improved in some second generation detectors. In the planned titania doped tantala/silica coatings, the less titania doped tantala, the lower the coating thermal noise will be. The amount of this material can be reduced without changing the reflectivity or any other optical property by optimizing the coating design[27] with respect to the amount of tantala. An optimized coating design will be used in Advanced LIGO, and is under consideration for Advanced Virgo and AIGO. Larger beam spot sizes also reduce coating thermal noise, so most second generation detectors have plans to increase the spot sizes. The ability to do this is limited by the size of the mirror and the acceptable amount of loss from light missing the mirrors. First generation interferometers typically had spot sizes of 3 to 5 cm, while second generation detectors will have spots closer to 6 cm.

3.5. *Quantum Noise*

Noise from the quantum nature of the light in the interferometer will be important at nearly all frequency bands of second generation detectors. Generally speaking, this is experienced as shot noise from photon counting at high frequencies (above about 200 Hz) and as radiation pressure noise from photon interactions with the test masses at low frequencies (below about 50 Hz). Signal recycling, however, mixes these two effects together and causes combined quantum noise to be at roughly the same level as coating thermal noise in the midfrequency band, depending on the signal recycling scenario. These two noise sources depend on optical power, as shot noise decreases at higher power while radiation pressure noise increases. First generation detectors were limited by shot noise at high frequencies but radiation pressure noise was not a limiting noise source. Increasing optical power is a primary goal of second generation detectors, up to the point where shot and radiation pressure noise are roughly equally limiting. Higher power lasers are the primary way this will be accomplished, going from 10 to 20 W of laser power in first generation instruments to 150 to 200 W in second generation. Such a large increase is necessary because both shot and radiation pressure noise (in amplitude) go as the square root of laser power. This increased laser power will make shot and radiation pressure noise at a similar level, but will also make thermal lensing[25] and parametric instabilities[22] more problematic in second generation than they were in first generation.

Radiation pressure noise manifests directly as a force noise, so with test mass position being the quantity sensed, larger mass optics can reduce radiation pressure noise without any offsetting effect on shot noise. First generation interferometers typically had test masses of about 10 kg, second generation masses will be about 40 kg (Advanced LIGO, Advanced Virgo, and AIGO) or 30 kg (LCGT). GEO HF will continue to use 5.5 kg test masses as was done in the first generation.

The inclusion of an additional mirror at the dark port of the interferometer allows for signal recycling[28] in second generation detectors. This mirror mixes the shot and radiation pressure noises in the output and allows for sensitivity better than the standard quantum limit in chosen frequency bands. By changing the reflectivity and/or the microscopic position of the mirror, the frequency and bandwidth where this noise improvement occurs can be altered at the expense of increased noise in other bands. This can be done to take advantage of other noise sources, by sacrificing sensitivity where the interferometer is limited by thermal noise, for example, in exchange for better sensitivity in the shot noise limited regime. It can also be used to optimize for a particular type of gravitational wave source, if the frequency distribution of the signal is known. Different signal recycling configurations are shown in Figure 7. This technique of signal recycling was used in the first generation by GEO 600 and will be used by all second generation interferometers.

Another technique to improve quantum noise is to squeeze the light into non-classical states. Shot and radiation pressure noise are due to phase and amplitude noise, respectively, in the light used to sense the position of the test masses. Phase and amplitude noise obey a Heisenberg relationship where the product must be more than roughly Planck's constant. Classical light has equal amounts of noise in each one of these at all frequencies. Squeezing allows for noise to be moved between phase and amplitude noise in the light, and hence shot and radiation pressure noise in the interferometer. If this can be done in a frequency dependant way, all quantum noise could be reduced across all frequency bands. Low levels of optical loss are needed throughout the interferometer otherwise the squeezed state is lost. Squeezing

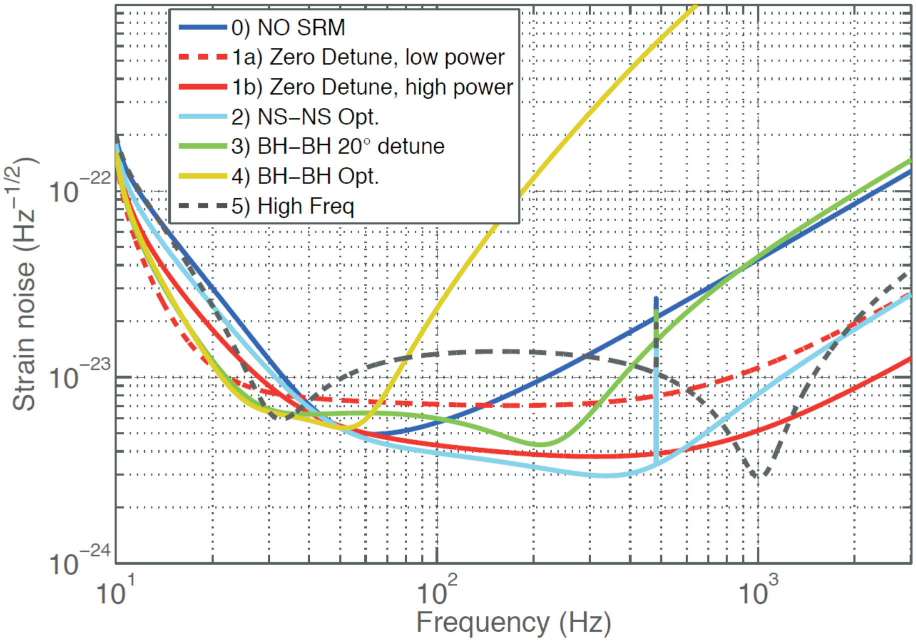

Fig. 7. Noise in Advanced LIGO in different signal recycling scenarios. The solid red curve could represent a baseline configuration where sensitivity is fairly good across a wide band. The light blue and yellow curves show quantum noise optimized for binary neutron star and binary black hole inspiral signals, respectively. The dashed black curve represents a narrowband tuning, which might be used to search for gravitational waves from a pulsar or other narrowband, continuous wave source.

has been demonstrated in laboratory settings at frequencies relevant for second generation gravitational wave detectors,[29] and is planned for use in GEO HF. All other second generation detectors are considering squeezing of light as a possible enhancement after some period of running with classical light.

3.6. *Ongoing Research*

Although most of the noise sources and important hardware for second generation detectors are well understood, there are some outstanding issues that are still areas of active research. One important topic is non-Gaussian noise, coming either from the external environment or the interferometer hardware. Glitches in the data proved a major limitation to first generation gravitational wave searches, especially for burst and inspiral events. It is hoped that this can be improved on in the second generation. Research areas include looking for correlations between data glitches and environmental disturbances in magnetic field, acoustics, microphones, etc; studying how to isolate the interferometer from excess noise from refrigerators needed to cool the test masses, vacuum equipment, and other necessary engineering hardware; and laboratory research on important materials like silica bonds and welds under mechanical stress, coatings under high optical power and thermal loading, and creep in the stressed steel used in seismic isolation and suspension subsystems.

The effects of high optical power on optics and other interferometer components is also an active area of research. This includes study of parametric instabilities,[22] where energy is exchanged between optical modes of a Fabry-Perot cavity and acoustic modes of a test mass. In some high power situations, test mass acoustic modes can ring up to the point where the interferometer becomes difficult to control and may even lose lock. High optical power also causes thermal lensing in the optics, which must be controlled. Thermal lensing[25] was a problem in many first generation detectors and is expected to need even more aggressive control in the second generation.

Cleanliness of optics is also receiving attention. It was found in some first generation detectors that optical absorption and scatter of the mirrors was higher than expected and may be related to contamination, either during installation or while operational. This was a nuisance in first generation detectors, but would be unacceptable in second generation ones. Improved techniques and quality controls are being developed to minimize this problem. Excess optical loss can lead to further problems with thermal lensing, perhaps beyond the ability of planned ring heaters and carbon dioxide laser subsystems to handle, and to destruction of squeezed light and subsequent increase in noise.

Build up of electrical charge on the test masses and other optics is also a concern in second generation detectors. Problems with charge on optics was seen in some first generation interferometers,[30] but only following catastrophic lock losses. Material changes, specifically replacing viton tipped earthquake stops with fused silica tipped ones, are expected to reduce charge transfer to the test masses during these violent events. Improved sensitivity in second generation instruments, however, will make them more sensitive to charge buildup, either as a direct source of noise or as a way of short circuiting seismic isolation. Research is underway on the use of ultraviolet light,[31] low energy ion guns,[32] and/or venting of vacuum chambers with charged gas as a way of mitigating charge problems.

4. Second Generation Project Status

Second generation detector projects are in varying states of funding and have different schedules for installation and commissioning, see Figure 8. For many projects, plans are still in development, so what is presented below is just a snap shot of the planning status at one particular time. Most projects are either funded or close to being funded, so there is confidence that a network of second generation detectors of comparable sensitivity will be built. The common goal is to take astronomically interesting data by about 2015.

United States National Science Foundation funding for Advanced LIGO construction and installation of hardware began in April 2008. In early 2010, Advanced

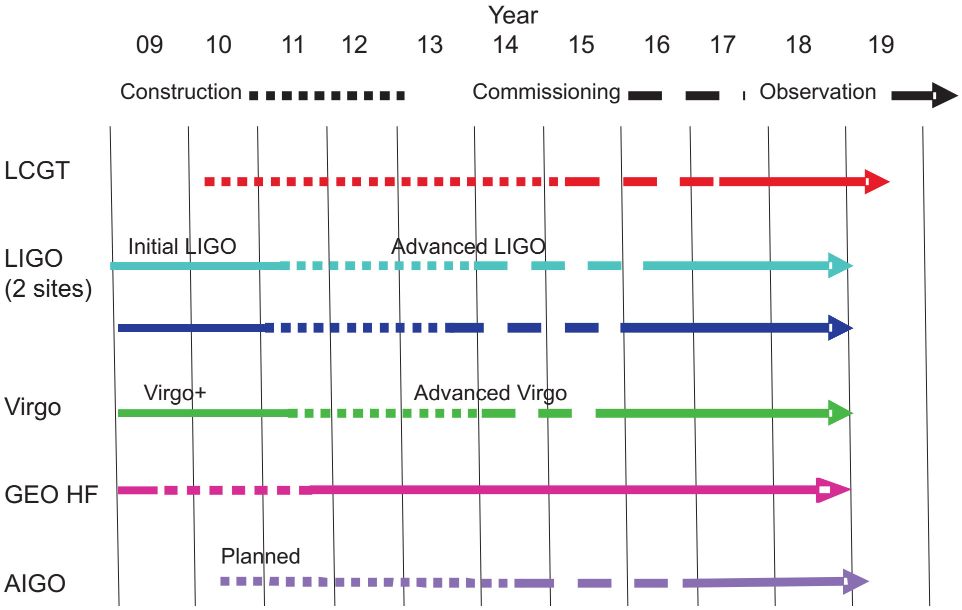

Fig. 8. Schedule for second generation gravitational wave detectors, showing periods of construction, commissioning, and operation. LCGT and AIGO are still just proposed projects, the others are funded.

LIGO is in a procurement and fabrication mode, buying and building hardware. Installation of new hardware is planned to begin in early 2011 at both sites and will continue until at least 2014. Prototyping of most hardware is well advanced; the LIGO Advanced Systems Test Interferometer (LASTI) at MIT is testing seismic isolation and suspensions, the 40 m prototype at Caltech is testing signal recycling for an Advanced LIGO configuration and squeezing, the Thermal Noise Interferometer also at Caltech has tested the new optical coatings, and the final runs of initial LIGO have tested some seismic hardware and a new readout scheme. Plans are in place to test squeezing on a full LIGO interferometer at Hanford in late 2010 just before Advanced LIGO installation. The Advanced LIGO schedule calls for first science runs as early as 2014.

Advanced Virgo was funded by the Italian funding agency Insituto Nazionale di Fisica Nucleare (INFN) and the French funding agency Centre National de la Recherche Scientifique (CNRS) in December of 2009. An enhancement to initial Virgo, called Virgo+, is running now. Monolithic silica suspensions are being installed in Virgo+ in 2010 as an upgrade and to prototype the design for Advanced Virgo. Procurement for Advanced Virgo hardware is now beginning in early 2010 and installation is expected to finish in 2014. Under this schedule, science data would be collected along with Advanced LIGO in 2015.

A proposal to fund the Large Cryogenic Gravitational Telescope (LCGT) was submitted to the Japanese funding agency in 2009 for funding in 2010. If approved, construction at the Kamioka site would begin immediately. Currently at Kamioka is the Cryogenic Laser Interferometer Observatory, CLIO, a 100 m prototype interferometer, which is testing both underground operation and cryogenics. The LCGT schedule calls for installation to be complete in 2014, followed by commissioning, and joint data taking with other second generation detectors in 2017.

The GEO HF detector is already funded by the Max Planck Institute in Germany and the Science and Technology Facilities Council in Britain. 2009 saw the installation of hardware to inject squeezed light into the interferometer in 2010. Towards the end of 2010 and in 2011 the installation of a higher power laser, a thermal compensation subsystem, and a new signal recycling mirror that will allow for higher bandwidth operation will occur. The expectation is that GEO HF will be ready to take science data from about 2012 onwards and as such will collect data in 2015 along with other second generation instruments.

The Australian International Gravitational Observatory (AIGO) is not yet proposed to the Australian funding agency, but plans are in place to submit a proposal soon. An 80 m prototype[33] at the Gingin site where AIGO might be built is already operating. It is testing parametric instability issues with high optical power and some possible AIGO hardware. International partnerships are being explored, with a laser from Germany already promised. Possible funding contributions from India and/or China are the topic of ongoing negotiations. Recently a suggestion to kick start AIGO using significant Advanced LIGO designs and possibly even hardware has been made. These possible collaborations will be discussed along with Australian funding for AIGO at a conference in Perth Australia in February 2010.

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