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Ground-based gravitational-wave detection: now and future

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Abstract
In the past three years, the first generation of large gravitational-wave interferometers has begun operation near their design sensitivities, taking up the mantle from the bar detectors that pioneered the search for the first direct detection of gravitational waves. Even as the current ground-based interferometers were reaching their design sensitivities, plans were being laid for the future. Advances in technology and lessons learned from the first generation devices have pointed the way to an order of magnitude improvement in sensitivity, as well as expanded frequency ranges and the capability to tailor the sensitivity band to address particular astrophysical sources. Advanced cryogenic acoustic detectors, the successors to the current bar detectors, are being researched and may play a role in the future, particularly at the higher frequencies. One of the most important trends is the growing international cooperation aimed at building a truly global network. In this paper, I survey the state of the various detectors as of mid-2007, and outline the prospects for the future.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction: looking forward and looking back

Conferences such as this one provide us with markers in time, helping us measure the changes that have taken place in our field and the progress we have made. This gathering, in particular, finds us at an important transition for gravitational-wave detection. Since the last Amaldi and GR meetings, we have seen a shift in the leadership in gravitational-wave observations. The current generation of acoustic detectors (‘bar detectors’), along the main observational instruments, have been surpassed in sensitivity by laser interferometer based detectors capable of extended observations. After more than two decades of development and construction, these interferometric detectors are now at the leading edge of ground-based gravitational-wave detection.

A second trend that I would like to emphasize is the growth in importance of detector networks. Although the oldest global network of gravitational-wave detectors, the International Gravitational Event Collaboration (IGEC), was established ten years ago, the past five years have seen an explosive growth in the level of collaboration and joint observations in the gravitational-wave community. Today, virtually every search for gravitational waves underway involves multiple projects collaborating across national and continental boundaries.

In this paper, I will summarize the capabilities of currently operating detectors and how these detectors are coming together to form a truly global network. I will describe the improvements which are underway or are planned for these detectors, and briefly outline the aspirations and dreams for the more distant future. I will not discuss the observational results to date, as these are covered in another plenary talk.

2. Bar detectors: the culmination of the first era in gravitational-wave detection

Bar detectors, resonant cylinders whose vibrational modes can be excited by the passage of a gravitational wave, hold a special place in the field of ground-based gravitational-wave detectors. J Weber built the first bar detector in the 1960s, creating from nothing the new field of gravitational-wave detection. Weber's initial announcement that he had observed gravitational waves [1] triggered an intense interest in gravitational waves, even though his findings were not confirmed by later experiments. As the field evolved over the next 40 years, at least 19 different bar detectors in 8 countries were built and used in searches for gravitational waves. A total of several hundred scientists, students, engineers and technicians were involved in this effort, and many of the current leaders in the field, including a number who now work on interferometric detectors, got their start working on bar detectors. The pioneering work of this community produced new understanding of important noise sources that can affect a variety of precision measurements: thermal/Brownian noise, back action/quantum noise, seismic/acoustic noise. It also produced a number of technological achievements in large cryogenic systems, low-noise displacement transducers and electronics. The exciting prospect that these detectors might see the first evidence of gravitational waves also triggered a corresponding interest in theoretical studies of possible sources, leading to much improved predictions of their strength. We now know that even the strongest gravitational waves incident on the surface of the earth (in the frequency bands where one can build sensitive ground-based detectors) typically have an intrinsic strain of 10^{-20} or less, corresponding to changes in lengths much smaller than the diameter of a proton even over kilometer-scale distances.

By 1997, in the absence of a confirmed detection, this large community has shrunk to just four groups operating five cryogenic bar detectors, but these groups initiated a new level of collaboration. Representatives of all five detectors came together in 1997 in Perth to create the first worldwide gravitational-wave network, the International Gravitational Event Collaboration (IGEC) [2]. IGEC included all operating bar detectors in the world: EXPLORER (CERN) NAUTILUS (INFN Frascati Laboratory), AURIGA (INFN Legnaro Laboratory), ALLEGRO (Louisiana State University) and NIOBE (University of Western Australia). The initial period of operation of IGEC [3] covered four years of coordinated observations from 1997 through 2000, resulting in 26 days of observation with four detectors taking data, 173 days of three-fold coverage and 707 days of two-fold coverage.

These initial data run by IGEC were followed by a series of upgrades to the different detectors. Major upgrades to the cryogenics, the suspensions, the tranducers and dc-SQUID amplifiers for EXPLORER and NAUTILUS were completed in 2000 and 2003, respectively,

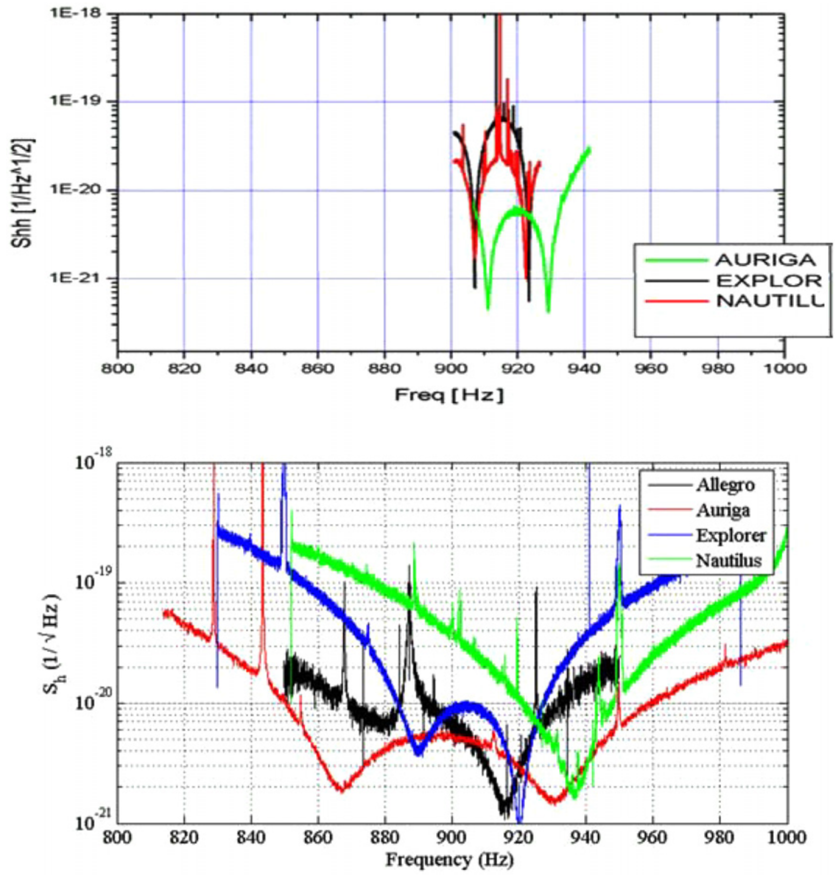

Figure 1. Strain sensitivity (noise level) versus frequency for the four current IGEC bar detectors. The top plot shows the sensitivities in the IGEC-1 run (1997–2000), while the bottom one shows the sensitivities as improved for the IGEC-2 run (2005-on). The improved bandwidth increases the sensitivity for broadband sources approximately proportion to the square root of bandwidth. (Figure courtesy of the IGEC-2 Collaboration [9] and reprinted with permission from Astone P *et al Phys. Rev.* D **76** 102001 (2007). Copyright 2007 by the American Physical Society.)

with a minor additional set of improvements for the EXPLORER transducer in 2004 [4]. From 2000 to 2003, AURIGA underwent a set of major upgrades, improving the suspension system for seismic isolation [5] and the readout system [6], resuming operation in late 2003. ALLEGRO received both a new resonant transducer and new readout electronics, and resumed operations in 2004 [7]. Although NIOBE underwent a series of improvements in 1998–2000 [8], it was forced to ceased operation in 2002 due to loss of funds, and the research group at UWA turned its focus toward interferometric detectors.

In 2005, the IGEC collaboration was reaffirmed, as IGEC-2, comprising the remaining four detectors. In all cases, one of the primary results of the upgrades was to increase the sensitive bandwidth of the detectors, which in turn led to increased sensitivity for broadband sources. A comparison of the IGEC-2 detector sensitivities with their IGEC-1 performance is shown in figure 1.

The first data analyzed by IGEC-2 covered a 6 month period—May–November 2005—when no other gravitational-wave observatory was operating [9]. This initial search included

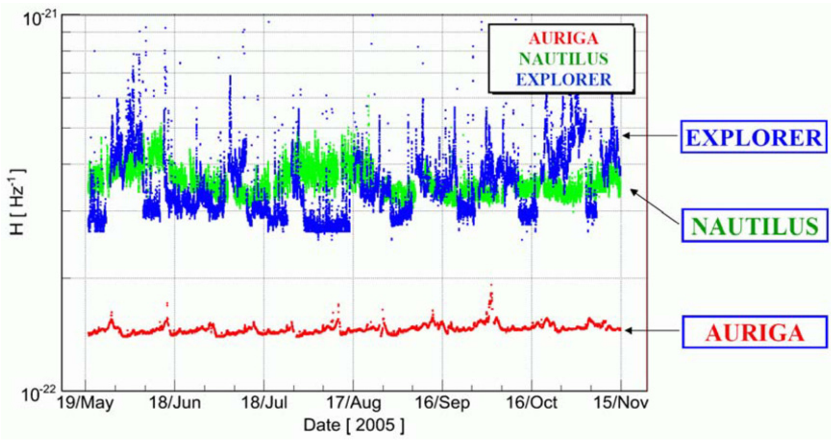

Figure 2. Strain sensitivity (noise level for a broadband source) versus time for the IGEC-2 detectors for the six month period between May and November 2005. The detectors showed excellent stability and up-time. (Figure courtesy of the IGEC-2 Collaboration [9] and reprinted with permission from Astone P *et al Phys. Rev.* D **76** 102001 (2007). Copyright 2007 by the American Physical Society.)

data from AURIGA, EXPLORER and NAUTILUS; ALLEGRO data quality flags were delayed and it was decided to use ALLEGRO data only for follow-up of any interesting events. As a result of the upgrades made after IGEC-1, the IGEC-2 detectors showed excellent duty factor and stability. During this period, the three analyzed detectors had an average duty factor of almost 90%, and the 180 days of observation produced 130 days of three-fold operation, almost as many as the earlier 4-year IGEC-1 data run. Figure 2 shows the stability and high duty factor for the IGEC-2 detectors during this 180 days period. The collaboration currently has a substantially larger set of data from 2006 to analyze. It is hoped that the data from ALLEGRO will be included in this analysis.

In spite of these successes, IGEC-2 has a cloudy future. Interferometric detectors (most notably LIGO) have now passed the sensitivity of bar detector and are beginning to approach them in observation time, making upper limits from generalized searches with the IGEC bar detectors significantly less interesting. (Note: searches for gravitational waves from extraordinary astrophysical events, such as a near-by supernova, can still be of great interest, particularly given less than full time coverage by interferometric detectors.) As a result, the supporting agencies have begun to limit or reduce the funding for bar detectors. NIOBE ceased operations in 2002 and it did not join IGEC-2. More recently, it was announced in April 2007 that the ALLEGRO detector would also soon cease operation, so its further participation in IGEC-2 will be restricted to previously collected data. AURIGA, EXPLORER and NAUTILUS continue to operate, but their continued funding will be evaluated annually.

3. Interferometric detectors: achieving their promise

A second major thrust in ground-based gravitational-wave detection [10] started only a few years after Weber's original announcement. Detectors based on laser interferometric measurements of the separation of freely falling test bodies (figure 3) offered some potential advantages. Because the strength of a gravitational wave is characterized by the strain it induces, the quantity measured by an interferometer (the apparent change in arm length)

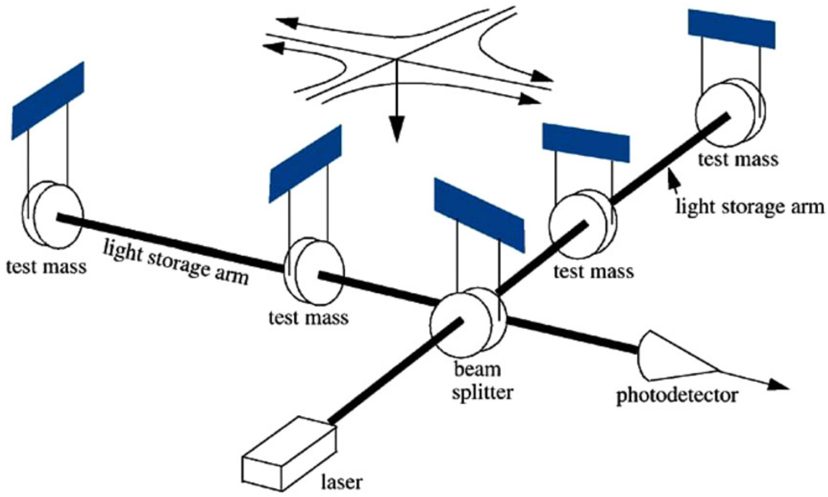

Figure 3. Schematic diagram of an interferometric gravitational-wave detector. This sketch shows a Fabry–Perot Michelson interferometer with power-recycling, the configuration used by LIGO, Virgo and TAMA. (Figure courtesy of the LIGO Laboratory.)

grows proportional to arm length, and thus increasing the arm length (up to one quarter of the gravitational wavelength) increases the signal relative to many of the important noise sources. In addition, the nature of an interferometer makes these detectors naturally cover a broad range of frequencies. However, there has been much technology to be developed to reach this promise, and the large detectors are both expensive and lengthy to build and commission. It is only in the last few years that the large interferometric detectors have taken the lead in sensitivity.

All of the current interferometric detectors are Michelson interferometers and most incorporate resonant Fabry–Perot cavities in the arms to enhance the sensitivity. A highly stabilized laser beam strikes the beamsplitter and is directed to the two arms. The interferometer is operated with constructive interference on the side of the beamsplitter which is illuminated by the laser (sending the light from the interferometer back toward the laser) and destructive interference on the other side where a photodetector reads out the difference in arm length (often called the 'antisymmetric port'). A partially transmitting mirror placed in the incident laser beam creates a second (compound) cavity, allowing the laser power incident on the beamsplitter to build up and increase the sensitivity of the interferometer. The interferometer mirrors are suspended in vacuum on thin wires from vibration-isolated platforms to protect them from non-gravitational forces which might interfere with the measurement. A complex control system maintains proper positioning and alignment of the optics. This configuration, dubbed a Fabry–Perot Michelson interferometer with power-recycling, is the basis for almost all current interferometric detectors.

The largest of these efforts is the Laser Interferometer Gravitational-wave Observatory (LIGO), located in the US [11, 12]. LIGO comprises two 4 km long L-shaped facilities, one at Hanford, Washington and the other in Livingston, Louisiana. The site at Hanford also has a 2 km detector sharing the same vacuum system. The LIGO detectors have the Fabry–Perot Michelson configuration with power-recycling. The laser is a 10 W Nd: YAG laser operating at 1.06 μm. The mirrors have a simple pendulum suspension with metal wires from a four-stage passive isolation system. The LIGO detectors were designed so that the dominant

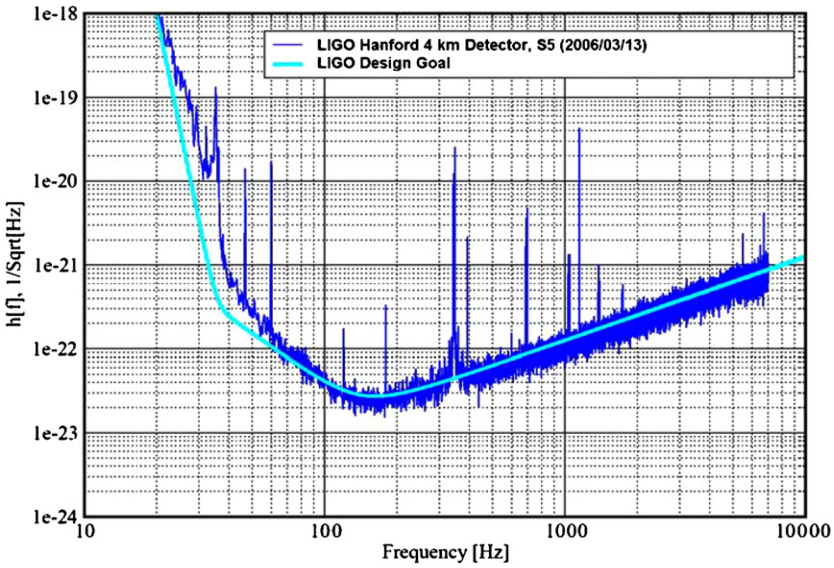

Figure 4. Strain sensitivity (noise level) versus frequency for one of the LIGO detectors, compared with the design goal. Except for a small range at low frequency, the detector meets or exceeds its goal. (Figure courtesy of the LIGO Scientific Collaboration.)

noise would be seismic motion at low frequencies, thermal noise at intermediate frequencies and shot noise at the highest frequencies, to provide a sensitive band between approximately 40 Hz and 6 kHz. Figure 4 shows the strain sensitivity of one of the LIGO detectors compared with its design goal. In 2005, the LIGO detectors reached their design sensitivity, for example, capable of detecting the inspiral and merger of a neutron star binary system out to the distance of the Virgo cluster of galaxies (depending upon orientation). In November 2005, LIGO began its fifth Science Run (S5) with the goal of collecting the equivalent of one full year of observation with all three of its detectors operating in coincidence. The LIGO research program is carried out by the LIGO Scientific Collaboration (LSC) with over 500 members at more than 50 institutions in 11 countries.

The German–British GEO collaboration has built GEO 600, an interferometer with 600 m arms located near Hannover [11, 13]. GEO 600 differs in its optical configuration from other interferometric detectors by not incorporating arm cavities. Instead, it uses a higher power-recycling factor and a technique known as signal recycling. In signal recycling, a partially transmitting mirror is placed in the output beam to cause a resonant build-up of the signal sidebands produced by the gravitational wave. The precise location of the signal-recycling mirror controls the frequency response of the interferometer (the frequency of maximum sensitivity) as illustrated in figure 5 [14]. GEO 600 also incorporates all fused silica suspensions (compared to the metallic wires of LIGO and Virgo) for low thermal noise. GEO has been a member of the LSC for a number of years and the GEO 600 detector operates in coordination with LIGO.

Virgo [15] is a French–Italian–Dutch collaboration that closely matches LIGO in scale and planned sensitivity. Virgo has a single 3 km interferometer at a facility near Cascina, Italy. It is a Fabry–Perot Michelson interferometer with power-recycling, with a 20 W Nd: YAG laser. Virgo also uses an optical cavity on its output to filter out higher order transverse modes at its antisymmetric port. One of the distinguishing features of Virgo is its advanced seismic

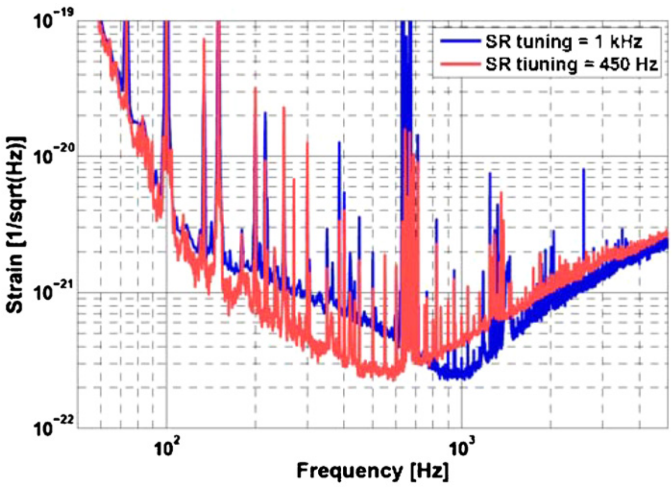

Figure 5. Strain sensitivity (noise level) versus frequency for the GEO 600 detector, showing how the sensitivity can be tailored by tuning the position of the signal-recycling mirror. (Figure courtesy of the GEO Collaboration and the Institute of Physics [14].)

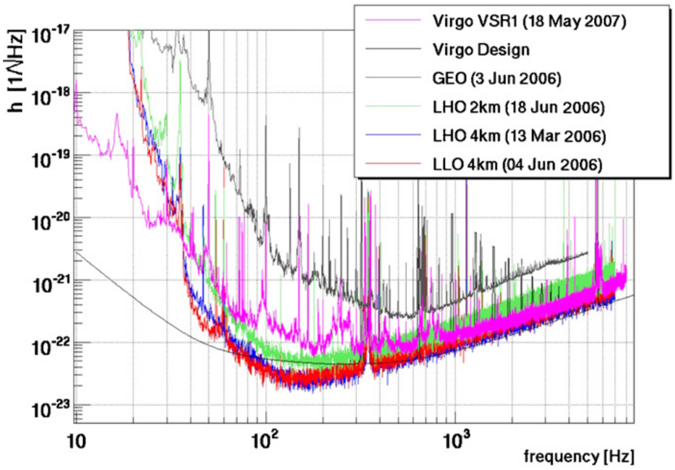

Figure 6. Strain sensitivity (noise level) versus frequency for the Virgo detector as it begins the VSR1 Science Run. The smooth curve shows the Virgo design goal, and representative sensitivity curves for the three LIGO detectors and GEO 600 from the same era are also shown. (Figure courtesy of the Virgo Collaboration.)

isolation system, the superattenuator [16]. A series of pendulum stages with vertical isolation springs provides very high attenuation of ground motion, effectively eliminating seismic noise as an important contributor to the Virgo noise budget above about 10 Hz. The final stage of suspension is metal wires as with LIGO. Virgo completed its first phase of commissioning and began its first extended scientific data taking (VSR1, Virgo Science Run 1) in May 2007. Its sensitivity (figure 6) matches that of LIGO at high frequencies, is about 3–5 times poorer in the mid-frequency band and exceeds that of LIGO at the lowest frequencies (below about 40 Hz).

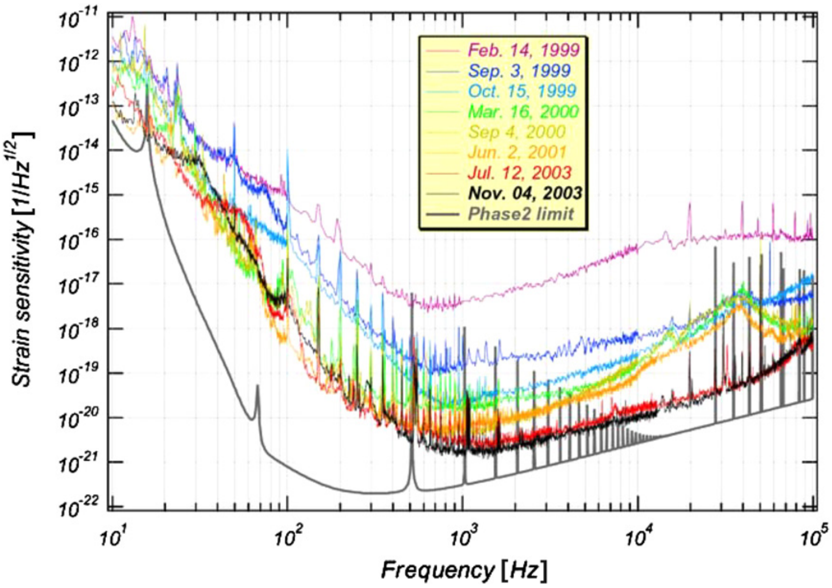

Figure 7. Strain sensitivity (noise level) versus frequency for the TAMA detector, as a function of time during its commissioning. In 2005, TAMA began installation of a new seismis isolation system. (Figure courtesy of the TAMA Collaboration.)

The beginning of the VSR1 marked another beginning. In the months leading up to VSR1, the Virgo Collaboration and the LSC negotiated a collaborative agreement. Under this agreement, all data analysis performed on data taken after the beginning of VSR1 would be analyzed and published jointly. Because of GEO's membership in the LSC, this agreement effectively brings together the five largest detectors in the world into a single network. The collaboration between Virgo and the LSC is specifically intended to be an open one, available to any other gravitational-wave detector which can make a significant addition to the scientific mission.

The first of the large interferometric detectors to operate in an observational mode was the TAMA detector [17] located at the National Astronomical Observatory of Japan (NAOJ). The project to build this 300 m long interferometer started in 1995. TAMA uses the Fabry–Perot Michelson configuration with power-recycling, similar to the optical design of LIGO and Virgo. TAMA's first data taking runs were started in 1999, interspersed with work to improve sensitivity. By 2000, TAMA had achieved the best sensitivity in world, a position it held until 2002 (see figure 7). In their sixth data taking run (DT-6) in 2001, TAMA achieved more than 1000 h of operation, with 86% duty factor [18]. Further detector improvements led to a second extended data taking (DT8) which was analyzed jointly with LIGO [19]. Even in the early experiments with TAMA, the need for better seismic isolation was recognized, because of the high seismic noise level at its urban location. A joint development was undertaken with members of the LIGO Laboratory for a new seismic attenuation system (SAS) for TAMA, based on the earlier Virgo concepts [20]. In 2005, installation of TAMA SAS was started and was completed in 2007. The TAMA collaboration is currently re-commissioning the detector and plans to start observations soon.

The final active collaboration seeking to build an interferometric detector is Australian. The Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) has begun the establishment of a site for the Australian International Gravitational-wave Observatory

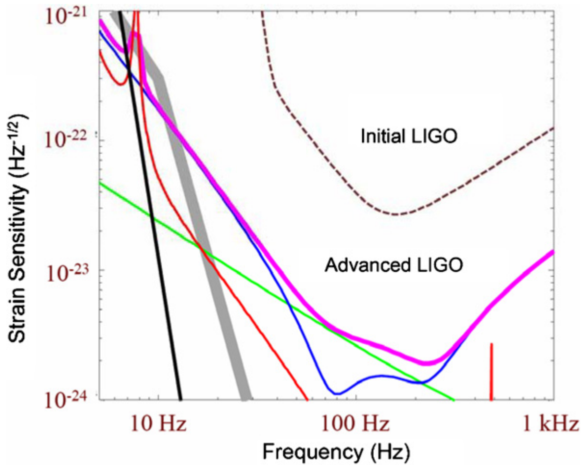

Figure 8. Design noise level for the Advanced LIGO detectors compared with the initial LIGO design goal. The advanced LIGO noise curve shown is the sum of numerous contributions: seismic noise, suspension thermal noise, mirror thermal noise, quantum noise and gravitational gradients. (Figure courtesy of the LIGO Scientific Collaboration.)

(AIGO) [21] on an 8 km by 8 km parcel at Gingin, Western Australia (70 km north of Perth). Construction began in 1999 and a substantial facility (including roads, clean room laboratories, workshops and a visitor accommodation) is now in place. An education and astronomy center opened in 2003. Currently, they are operating an 80 m long interferometer for testing the effects of high optical power, in support of the Advanced LIGO program [22].

4. Looking toward the future

The successes of the various interferometric detector projects around the world have set the stage for an ambitious program of second generation detectors. The largest of these is Advanced LIGO [23], an upgrade to the existing LIGO detectors which has been approved and is awaiting first funding. Advanced LIGO is designed to take advantage of new technologies and on-going R&D leading to a substantial increase in sensitivity and bandwidth over the existing LIGO detectors. Virtually every part of the LIGO detectors, except the facilities and the vacuum system, will be replaced. New active anti-seismic system, operating to lower frequencies, will provide the platform for the detectors. Lower thermal noise suspensions incorporating multiple pendulums and all fused silica final stages, provided by the GEO collaboration, will be used. New low loss optics and a higher power laser (provided by the GEO Collaboration) will improve noise in the high frequency regions currently limited by shot noise. The Advanced LIGO optical configuration includes a signal-recycling mirror to improve the sensitivity and to be able to tailor the sensitivity as a function of frequency to target particular types of sources.

The expected improvement in sensitivity of Advanced LIGO is shown in figure 8. In the most sensitive region Advanced LIGO will have a factor of 10 better sensitivity to gravitational-wave strain. This improvement translates into a ten times larger range to detect sources, or a factor of one thousand larger volume. The extension of the sensitive frequency band to lower frequencies also greatly broadens the range of sources which may be detected. The operation of Advanced LIGO and the other comparable detectors described below, will move the field from gravitational-wave detection to gravitational-wave astrophysics. Construction of Advanced LIGO is planned to start in 2008, start with installation in the existing LIGO vacuum system beginning in 2011.

This schedule for Advanced LIGO leaves more than 3 years before the initial LIGO detectors must be removed. This is enough time for one significant set of enhancements to the initial LIGO detectors. This project, called Enhanced LIGO, aims for a factor of 2 improvement in sensitivity over initial LIGO, corresponding to a factor of 8 in the volume of the universe observed. The main technical elements of Enhanced LIGO include a higher power laser (35 W versus the current 10 W), and a change in the readout scheme for the interferometer. The readout of the interferometer will be changed from an rf scheme using phase modulated sidebands to a dc readout scheme using a tiny offset from the dc fringe minimum. An output modecleaner will be added to eliminate higher order transverse modes from the light incident on the photodetectors. Enhanced LIGO will give early tests of some Advanced LIGO hardware and techniques, thus reducing the risk and raising the probability of success of Advanced LIGO.

Virgo has a similar two-phase plan for future upgrades [24]. Following the completion of their current data taking (VSR1) in late 2007, the Virgo Collaboration will undertake Virgo+, a set of improvements designed to give at least a factor of 2 sensitivity increase over nominal initial Virgo design goal. Virgo+ is an intermediate step toward Advanced Virgo, which will have a ten times sensitivity increase over nominal Virgo. Building and commissioning Virgo+ will continue upto mid 2009, to be followed by another extended data run in coincidence with Enhanced LIGO, lasting into late 2010. Advanced Virgo fabrication will be carried on in parallel with Virgo+ commissioning and operation and Advanced Virgo installation will begin in 2011.

The final technical scope of Virgo+ and Advanced Virgo is still not fully determined. Current plans for Virgo+ include an increase in laser power, a change in the finesse of the arm cavities, the addition of a system to compensate for optical heating in the mirrors, and elimination of several sources of excess noise at low frequencies. Advanced Virgo [24] will include a major upgrade for all nearly all Virgo subsystems. Larger mirrors with improved coatings will be installed to reduce radiation pressure noise and coating thermal noise. Still-higher laser power will be used, and the thermal compensation systems installed for Virgo+ will be upgraded to operate at the higher level. A signal-recycling mirror will be added. The Virgo superattenuator seismic isolation will be retained but the final stage suspension will be upgraded to an all fused-silica configuration. The enabling R&D for these upgrades is already underway, and the crucial design decisions will be made in late 2007.

GEO 600 will be upgraded through a project known as GEO-HF [25]. GEO's upgrade plans are constrained by its shorter arm length and the inability to expand its site because of geographic limits (a river). These constraints mean that it would be unlikely that GEO can match the sensitivity of Advanced LIGO and Advanced Virgo at low frequencies. As a result, GEO upgrades will concentrate on improving its sensitivity at high frequencies, near 1 kHz. Potential sources of gravitational waves in the frequency band from 1 to 5 kHz include bursts of gravitational waves from supernovas, normal modes of neutron stars and quasi-normal modes of stellar mass black holes. The GEO-HF laser will be upgraded to a higher power version, similar to the one being developed by the GEO collaboration for Advanced LIGO. Signal recycling will be retained and may be tuned to offer a narrower bandwidth. New mirrors may be installed to reduce thermal noise. A second goal of GEO-HF is to pioneer advanced techniques which may be applied later to other large interferometers. This might include use of squeezed states of light to enhance sensitivity [26]. These upgrades will be

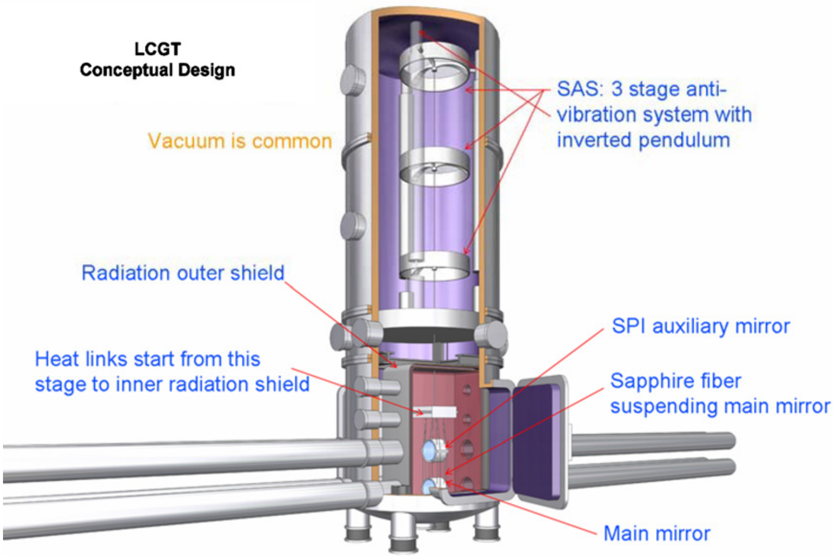

Figure 9. Schematic drawing of the cryogenic suspension planned for LCGT. (Figure courtesy of the LCGT Collaboration.)

implemented as opportunities present themselves between now and 2010, in coordination with the run planning for LIGO and Virgo.

The Japanese groups who designed and built TAMA have proposed an ambitious new detector: the large-scale cryogenic gravitational-wave telescope (LCGT) [27]. LCGT would be located at an underground site (the Kamioka mine) and will have 3 km long arms. It will have the same basic optical layout as TAMA (Fabry–Perot Michelson with power-recycling), but resonant sideband extraction [28] will be used to increase sensitivity and to be able to tailor the frequency response. Two parallel interferometers will be installed in a common vacuum envelope, similar to the LIGO Hanford site. The main technical feature which distinguishes LCGT from Advanced LIGO and Advanced Virgo is that the LCGT mirrors will be cooled to cryogenic temperatures to reduce thermal noise (figure 9). The seismic isolation/mirror suspension system will be similar to the upgraded system seismic attenuation system (SAS) recently installed in TAMA, and much progress has been made in the development of cryo-coolers which can extract the required heat load without introducing unwanted vibrations [29]. The detector will incorporate a suspension point interferometer to isolate from low frequency seismic motion. CLIO, a 100 m interferometer to demonstrate the cryogenic technology and the benefits of an underground location has been built in Kamioka mine [27]. A proposal for 2008 funding LCGT has been recently turned down (between the presentation of this talk and the preparation of the proceedings paper) and the LCGT collaboration is considering its further options.

ACIGA is pursuing funding to expand the Australian International Gravitational-wave Observatory (AIGO) to kilometer scales. The location in Western Australia offers strong science benefits in the context of an international network. The long baseline to planned detectors in the US and Europe improves the effective angular resolution for bursts of gravitational waves (such as might be emitted by the merger of a neutron star binary) from the order of a degree to about 10 arc minutes [30]. With this resolution, it will be possible to make unique galaxy identifications out to nearly 100 Mpc. The AIGO goal is to have 5 km

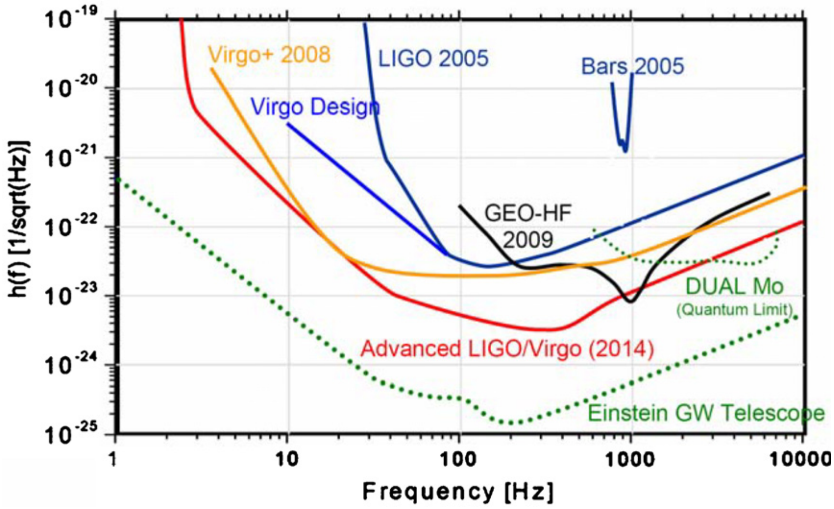

Figure 10. Possible noise level for the Einstein Gravitational-Wave Telescope compared with the other current and planned detectors. (Figure courtesy of the ET Collaboration.)

arms and to be sensitive to inspirals in the range ∼250 Mpc. The Western Australian Government has provided seed funding for AIGO by establishing a Centre of Excellence for Gravitational Astronomy and the Australian Consortium is actively seeking funding including new international partners in this project.

For the more distant future, the interferometric detector community is contemplating a detector called the Einstein Gravitational-Wave Telescope (ET). The sensitivity goals for ET are shown in figure 10, aiming at another factor of 10 sensitivity beyond Advanced LIGO and Advanced Virgo, as well as a much lower frequency capability. The ET baseline concept incorporates two of the innovative features of LCGT: an underground location and cryogenic cooling. The underground location is important to reduce seismic noise and to reduce gravity gradient noise. Cryogenic cooling of mirrors offers the possibility of lower thermal noise. Ultra-low frequency suspensions would be required to take advantage of the lower thermal noise, and quantum non-demolition techniques [26, 31] are likely to be employed. Configurations under consideration for ET include triangular ones in addition to the L's of the first- and second-generation interferometric detectors. Cost considerations will be important and the current studies are constrained to have an overall beam tube length of ∼30 km. Currently, ET is the subject of a design study funded by the European Commission, but it is expected that the broader ground-based interferometric detector community will be involved to some extent.

Finally, even as the current generation of cryogenic bar detectors is reaching its end, there are ideas for new directions. The AURIGA group has been exploring a new concept for acoustic gravitational-wave detectors that they call DUAL [32]. DUAL envisages two nested mechanical resonators (shown in the right portion of figure 11 as two cylinders). In the region between the main resonant modes of the two cylinders, the motion in the gap between the two masses is out of phase. By combining the output of a set of non-resonant transducers placed in the gap, on can read the differential deformations of the cylinders, throughout the frequency band between the two resonances. By combining the outputs of multiple sensors in the correct way, the result is a system that is sensitive only to the motion corresponding to gravitational

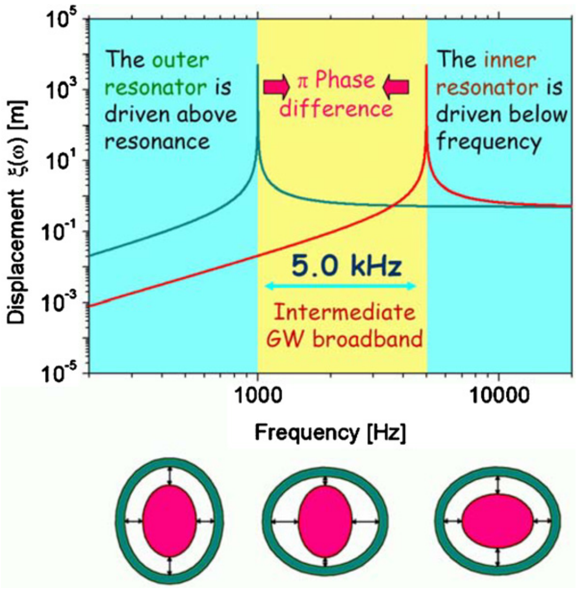

Figure 11. Illustration showing the DUAL detector operation. The two nested oscillators in the lower part of the figure illustrate how it operates: above and below both resonances the two oscillators respond to a gravitational wave with the same phase, but between the two resonances they respond out of phase. Transducers in the gap will sense the differential motion. (Figure courtesy of the DUAL Collaboration.)

waves, and which reduces overall thermal noise by rejecting the contribution of modes which are not sensitive to gravitational waves.

There are a number of questions which must be resolved before construction of a full-scale DUAL detector could begin, and research is underway to address many of these. Alternate physical configurations to the cylindrical one in figure 11 are possible, and several materials are being evaluated for their physical properties and manufacturability. The selection of the readout is critical; large area readouts are important for back-action reduction and mode selectivity. Current candidates include optical readouts [33] and capacitive readouts with SQUID amplifiers. If the R&D for these detectors is successful, they may provide complementary coverage to the large interferometers in the frequency band from 1 to 5 kHz.

5. Final thoughts

Over the past decade, we have seen remaining bar detectors around the world mature and coalesce into a coherent network. Since the last International Conference on General Relativity & Gravitation, we have also seen interferometric detectors equal and pass the bar detectors in sensitivity, taking the leadership in the field of ground-based gravitational-wave detection. Interferometers are now showing the sensitivities and bandwidths that they promised, and the interferometer projects have begun to organize themselves into a global network. Improvements to the existing interferometric detectors are underway, and next generation detectors will soon be under construction. Together these improvements offer to increase our ‘science’ capability by a factor of 1000 or more. The day when we see the first direct detection of gravitational waves draws steadily nearer.

Acknowledgments

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References

[1] Weber J 1969 *Phys. Rev. Lett.* **22** 1320–4
Weber J 1970 *Phys. Rev. Lett.* **25** 180–4
[2] Allen Z *et al* 2000 *Phys. Rev. Lett.* **85** 5046
[3] Astone P *et al* 2003 *Phys. Rev.* D **68** 022001
[4] Astone P *et al* 2003 *Phys. Rev. Lett.* **91** 111101
Astone P *et al* 2006 *Class. Quantum Grav.* **23** S57
[5] Bignotto M, Bonaldi M, Cerdonio M, Conti L, Penasa F, Prodi G, Soranzo G, Taffarello L and Zendri J 2005 *Rev. Sci. Instrum.* **76** 084502
[6] Baggio L *et al* 2005 *Phys. Rev. Lett.* **94** 241101
[7] McHugh M P, Johnson W W, Hamilton W O, Hanson J, Heng I S, McNeese D, Miller P, Nettles D, Weaver J and Zhang P 2005 *Class. Quantum Grav.* **22** S965
[8] Coward D, Blair D, Clay R and Mazzitell G 2002 *Class. Quantum Grav.* **19** 1871–5
[9] Astone P *et al* 2007 *Phys. Rev.* D **76** 102001
[10] Weiss R Quarterly Progress Report 105, Research Laboratory of Electronics, MIT, April 1972
Moss G F, Miller L R and Forward R L 1971 *Appl. Opt.* **10** 2495–8
[11] Abbott B *et al* (LIGO Scientific Collaboration) 2004 *Nucl. Instrum. Methods* A **517** 154–79
[12] Sigg D (for the LIGO Scientific Collaboration) 2006 *Class. Quantum Grav* **23** S51–6
Sigg D (for the LIGO Scientific Collaboration) 2007 Status of the LIGO detectors *Class. Quantum Grav.* **25** 114041
[13] Grote H (for the LIGO Scientific Collaboration) The Status of GEO 600 *Class. Quantum Grav.* **25** 114043
[14] Willke B (for the LIGO Scientific Collaboration) 2007 *Class. Quantum Grav.* **24** S389–97
[15] Acernese F *et al* 2004 *Class. Quantum Grav.* **21** S385–94
Acernese F *et al* 2007 *Class. Quantum Grav.* **24** S381–8
[16] Del Fabbro R, Di Virgilio A, Giazotto A, Kautzky H, Montelatici V and Passuello D 1987 *Phys. Lett.* A **124** 253–7
Braccini S *et al* 1995 *Phys. Lett.* A **199** 307–14
Beccaria M *et al* 1997 *Instrum. Methods* A **394** 397–408
Braccini *et al* 2005 *Astroparticle Phys.* **23** 557–65
[17] Ando M *et al* 2001 *Phys. Rev. Lett.* **86** 3950
Kuroda K (for the TAMA Collaboration) 2007 The current status of TAMA *Proc. Rencontres de Moriond, Gravitational Waves and Experimental Gravity (La Thuile, Val d'Aosta, Italy, March 11–18, 2007)* at press
[18] Takahashi H *et al* 2004 *Phys. Rev.* D **70** 042003
[19] Abbott B *et al* (LIGO Scientific Collaboration) and Akutsu T *et al* (TAMA Collaboration) 2005 *Phys. Rev.* D **72** 122004
Abbott B *et al* (LIGO Scientific Collaboration) and Akutsu T *et al* (TAMA Collaboration) 2006 *Phys. Rev.* D **73** 102002
[20] Márka S *et al* 2002 *Class. Quantum Grav.* **19** 1605–14
Takamori A *et al* 2002 *Class. Quantum Grav.* **19** 1615–21
[21] Zhao C *et al* 2006 *J. Phys.: Conf. Ser.* **32** 368–73
[22] Ju L *et al* 2004 *Class. Quantum Grav.* **21** S887–93
Barriga P *et al* 2005 *Class. Quantum Grav.* **22** S199–208

[23] Fritschel P 2003 Second generation instruments for the Laser Interferometer Gravitational Wave Observatory (LIGO) *Gravitational-Wave Detection* vol 4856 ed M Cruise and P Saulson (Bellingham, WA: SPIE) 282–91
Robertson N A *et al* 2004 Gravitational wave and particle astrophysics detectors *Proc. SPIE* ed Hough J and Sanders G **5500** 81–91
Miyakawa O *et al* 2004 Gravitational wave and particle astrophysics detectors *Proc. SPIE* ed Hough J and Sanders G H **5500** pp 92–104
[24] The Virgo Collaboration 2007 Advanced Virgo Conceptual Design Virgo Report VIR 042A 07, http://wwwcascina.virgo.infn.it/advirgo/docs/AdV_Design.pdf
[25] Willke B *et al* 2006 *Class. Quantum Grav.* **23** S207–14
[26] McKenzie K, Grosse N, Bowen W P, Whitcomb S E, Gray M B, McClelland D E and Lam P K 2004 *Phys. Rev. Lett.* **93** 161105
Vahlbruch H, Chelkowski S, Hage B, Franzen A, Danzmann K and Schnabel R 2006 *Phys. Rev. Lett.* **97** 011101
[27] Uchiyama T *et al* 2004 *Class. Quantum Grav.* **21** S1161–72
Kuroda K (for the CLIO/LCGT Collaboration) 2007 CLIO and LCGT *Proc. Rencontres de Moriond, Gravitational Waves and Experimental Gravity (La Thuile, Val d'Aosta, Italy, March 11–18, 2007)* at press
[28] Mizuno J, Strain K A, Nelson P G, Chen J M, Schilling R, Ruediger A, Winkler W and Danzmann K 1993 *Phys. Lett.* A **175** 273
Strain K A *et al* 2003 *Appl. Opt.* **42** 1244
Miyakawa O *et al* 2006 *Phys. Rev.* D **74** 022001
Kawazoe F, Sato S, Leonhardt V, Miyakawa O, Morioka T, Nishizawa A, Yamazaki T, Mitsuhiro Fukushima M, Kawamura S and Sugamoto A 2007 Experimental investigation of a control scheme for a tuned resonant sideband extraction interferometer for next-generation gravitational-wave detectors (submitted to *Class. Quantum Grav.*)
[29] Li R *et al* 2004 *Class. Quantum Grav.* **21** S1005–8
[30] Wen L, Howell E, Coward D and Blair D 2007 *Proc. Rencontres de Moriond, Gravitational Waves and Experimental Gravity (La Thuile, Val d'Aosta, Italy, March 11–18, 2007)* at press
[31] Kimble H J, Levin Yu, Matsko A B, Thorne K S and Vyatchanin S P 2002 *Phys. Rev.* D **65** 022002
Purdue P 2002 *Phys. Rev.* D **66** 022001
Purdue P and Chen Y 2002 *Phys. Rev.* D **66** 122004
Chen Y 2003 *Phys. Rev.* D **67** 122004
[32] Cerdonio M, Conti L, Lobo J A, Ortolan A, Taffarello L and Zendri J P 2001 *Phys. Rev. Lett.* **87** 031101
Bonaldi M, Cerdonio M, Conti L, Pinard M, Prodi G A, Taffarello L and Zendri J P 2003 *Phys. Rev.* **68** 102004
[33] Marin F, Conti L and De Rosa M 2003 *Phys. Lett.* A **309** 15–23