Chapter 1

Present and future detectors

1.1 Ground based interferometric gravitational wave detectors

1.1.1 *History of ground-based interferometric gravitational wave detectors*

Given the size of the LIGO project and of the LSC community, and the pivotal role they played in the history of the filed and eventually in the first detection of gravitational wave, we will use the LIGO detectors as the leading example, and highlight how the other projects compared with it both technically and strategically. We want to stress that the comparatively small amount of space and detail dedicated to other projects does not reflect the importance of the role they have played and still play in the field.

The history of gravitational wave detection is one of fiendishly bright ideas, perseverance in the face of incredible technical challenges, and the growth of a global community of scientists focused on a singular goal of detecting gravitational waves and using them to learn more about the universe. At the time of writing the first part of this charge was recently achieved, with the detection of a gravitational wave signal unmistakably generated from a binary black hole coalescence by the Advanced LIGO detectors on the 15th of September 2015 [Abbott *et al.* (2016)]. To some this achievement is the culmination of many years of hard work and dedication. To others, this is merely the beginning of a new era of gravitational wave astronomy.

The very earliest history of interferometric gravitational wave detectors lies in the experiments of the American physicists Albert Michelson and Edward Morley in the summer of 1887. Although the goal of the famous Michelson-Morley experiment was not to detect gravitational waves (indeed the theory that predicts their existence was still several decades away from being conceived), the basic design of their apparatus can still be found in every ground-based interferometric gravitational wave detector. Michelson and Morley used their interferometer to attempt to measure variations in the speed of light with direction of propagation, and as a result to measure the velocity of the Earth with respect to the luminiferous aether: a feature of the prevailing physical theories of the time. By the time of their 1887 measurement, their apparatus was deemed capable of measuring shifts of about 1% of a fringe; a remarkable feat given the technology available.

The negative results of the Michelson-Morley experiment eventually paved the way for Einstein's theory of special relativity, in which the speed of light is invariant with propagation direction. It is somehow fitting that a variant of the same apparatus was used in 2016 to make the first direct measurement of gravitational waves, themselves a key prediction of Einstein's theory of general relativity.

Efforts to detect gravitational waves began in earnest with Joseph Weber's development of resonant bar detectors in the 1960s. This detection scheme relied on the excitation of resonant modes of a mass with a high mechanical quality factor by passing gravitational waves. The reliance on resonances of the test mass produced a detector with an extremely limited bandwidth, able only even in principle to detect the presence of a GW signal, and not to uncover detailed information about the nature of the sources of the waves. Weber reported a series of detections throughout the 1960s. Efforts by Richard Garwin, Heinz Billing and others to reproduce his results were fruitless, however, and by the 1970s the veracity of Weber's detection claims was widely doubted.

In the 1960s the idea of using laser interferometers as gravitational wave detectors was developed more or less simultaneously in several places, by Joseph Weber himself, along with soviet physicists Mikhail Gertsenshtein and Vladislav Pustovoit. It was not until 1972, however, that Rainer Weiss first performed a detailed noise analysis of a laser interferometer in the context of gravitational wave detection, considering all of the fundamental noise sources that still limit detectors to this day [Weiss (1972)]. It was this study that really demonstrated the feasibility of using large-scale laser interferometers for gravitational wave detection, and it was instrumental in securing funding for the further development of the technology, prototype interferometers, and eventually LIGO itself. The late 1960s through the early 1990s was the era of prototype interferometric gravitational wave detectors, beginning with Robert Forward (a former graduate student of Weber) [Forward (1978)], through Weiss' prototype at MIT [Dewey *et al.* (1984)], the Garching prototype developed by Heinz Billing and others [Shoemaker *et al.* (1988)], and a prototype in Glasgow lead by Ronald Drever and James Hough [Robertson *et al.* (1995)]. It was clear from Weiss' initial study that although reaching the required sensitivity to detect gravitational waves was possible in principle, a huge technological effort would be required to make that potential a reality. Prototype detectors were an essential part of that technology development. Funding a full-scale observatory was still deemed too risky during this era, and in any case the technology simply was not at a mature enough stage to give them a reasonable chance of detecting gravitational waves. These prototypes also provided the function of training young scientists in the methods and concepts that would be instrumental in designing, building and operating gravitational wave detectors.

At the beginning of the 1980s the two projects that would eventually join together to form LIGO were initiated: a design study for a kilometer scale interferometer at MIT, and a 40 m prototype interferometer at Caltech [Spero (1989)]. Work continued on these projects, and the LIGO project persistently applied for funding through the late 1980s.

In 1992, NSF approved funding for the construction of the two experimental facilities of the LIGO (Laser Interferometer Gravitational-wave Observatory) project[Abramovici *et al.* (1992)], to be built and operated jointly by MIT and Caltech. After a short period, however, it became clear that the LIGO team did not have the expertise and organizational skills to manage a project of that size, and funding was frozen following a review from a NSF oversight panel. The situation was solved in winter 1994, when Barry Barish was appointed director of the project. Drawing on his previous experience with large scale scientific projects, Barish and his team put together a comprehensive and convincing management plan. The revised plan, that among other things increased the cost estimate from 250 to more than 290 million dollars, was approved again in 1994, despite skepticism and some strong opposition from part of the physics and astronomy communities. Many thought that the investment, the largest ever made by NSF on a single project, was too risky, that it would needlessly drain resources from other research (which in fact did not happen, mostly thanks to the able political and financial planning of the NSF director Eric Bloch), and that the chances of success would be almost non existent. History would eventually prove them wrong.

Ground was broken in winter 1994 in Hanford, WA, and the following year in Livingston, LA; the construction of the buildings and of the vacuum system, by some measures the biggest ever built at the time, took almost five years. Separated by more than 3000 km, the two experimental sites shared the same basic design: a 4 km long L shape structure; they however differed in orientation (both have one arm aligned with the great circle joining the two sites, but the other arms are anti-parallel), and for the fact that the one in Hanford was designed to accommodate two parallel interferometers, 2 km and 4 km long respectively, in the same vacuum system. The installation of the scientific equipment started in 1999 and was completed by the end of 2000. In the meantime, a broader scientific community had grown around the LIGO project, and had taken the shape of two institutions: the LIGO laboratory, in charge of managing the facilities and most of the research and development directly aimed at improving the instruments, and the LIGO Scientific Collaboration (LSC), formed by research groups around the world involved in technical and scientific research related to LIGO.

While construction of the two LIGO detectors was ongoing in the US, parallel efforts were being pursued in Europe. A French-Italian collaboration secured funding from CNRS and INFN for a similar facility to be built in Cascina, near Pisa, Italy. The construction of the 3-km long Virgo interferometer started in 1996 and was completed in 2003. During this period, the European Gravitational Observatory (EGO) consortium was created to operate the detector and promote gravitational research in Europe.

The UK and Germany also joined forces to build a large scale interferometer; the full-size project was not funded, but was de-scoped to a slightly smaller version named GEO600 (due to its 600 meters long arms), whose construction near Hannover, Germany, started in 1995. Despite its smaller size and consequent limited sensitivity, over the years GEO600 played a fundamental role in pioneering many innovative technologies that would later be integrated in the larger interferometers. Depsite being two separte scientific project, LIGO and GEO operated in close collaboration from the very beginning, and the members of the GEO600 project were also founding members of the LSC.

Smaller scale interferometers, mainly intended as prototypes, were built or proposed in other parts of the world. In particular, ACIGO in Australia and CLIO and TAMA300 in Japan. CLIO was the first detector to implement cryogenic operation and demonstrate a reduction in thermal noise, although its limited size did not allow it to reach a competitive sensitivity for gravitational wave detection[Uchiyama *et al.* (2012)].

As the various interferometers around the world started to come online, and ambitious plans were laid out to build even more powerful ones, the growing gravitational wave community started to realize that close international collaboration would be essential to success. While exchange of expertise and experiences would help a faster and more efficient development and commissioning of the detectors, their joint operation and data analysis would be the key to extract the maximum science from any detection and enable the entire field of gravitational wave astronomy to flourish. LIGO and GEO600 were close partner from the beginning, and both member of the LSC; interaction between the LSC and the Virgo community grew closer and closer during the 2000s, resulting in the creation of the LIGO Virgo Scientific Collaboration (LVSC) which enabled free exchange of technical expertise and research, common data analysis efforts and coordinated joint observation runs. On a less formal basis, the same happened with other GW communities around the world.

1.1.2 *Design and operation of the first generation of interferometric gravitational wave detectors*

In this and the following sections we describe the initial generation of ground based gravitational wave detectors and their subsequent major upgrade, often referred to as second generation. While this classification matches closely the upgrade history of the two largest scale interferometers, LIGO and Virgo, this may not necessarily be the case for other detectors that adopted different upgrade strategies or started development later. For these interferometers, the distinction that we make here between first and second - or even future - generations is to some degree arbitrary.

Despite the extensive research and development effort put forward and the experience acquired over several years on smaller prototypes, it was clear to the gravitational wave community and to the funding agencies that building and operation of km-scale interferometers at their design sensitivity was a high risk, although potentially high gain, endeavor. The first generation of interferometers were designed to be relatively simple, reducing the odds of an actual detection but increasing the chances of their successful commissioning and operation. In particular, while the adopted topology was very similar to the one used in the subsequent generation, the complexity of many subsystems were kept to a minimum. The detector infrastructures constituted the bulk of the initial budgets however, and were built to be able to support future upgraded detectors

The initial LIGO detectors[Abbott *et al.* (2004, 2009)] were power-recycled, Fabry-Pérot Michelson interferometers. An out-of-vacuum, 10 W, 1064 nm Nd:YAG pre-stabilized laser was phase modulated to add three sets of sidebands for alignment and sensing control. The beam was then spatially filtered and further stabilized in power and frequency by an in-vacuum input-optics section: this included a 24 m round-trip suspended triangular optical cavity, referred to as input mode cleaner, a low loss Faraday isolator, and a suspended telescope to match the beam mode to that of the rest of the interferometer. The beam was then injected into the recycling cavity, which increased the input power seen by the rest of the interferometer by a factor of about 50; finally, the power reached about 20 kW in the impedance matched arm cavities, designed to have a finesse of 220. There was no signal recycling cavity, and the strain signal was obtained using RF readout of the interferometer output.

The vacuum system layout, also designed to accommodate subsequent upgrades of the detectors, was based on a series of vacuum chambers of either of two types: horizontal ones, for the input and output optics, and vertical ones for the core optics. Both type are cylinders about 2 m in diameter and 3 m in height, with large access ports for easy installation of heavy equipment. The corner station at the Livingston observatory hosts 6 horizontal chambers, 3 on the input and 3 on the output branch, and 3 vertical chambers, with another two hosted in the end stations. All chambers, including the ones at the end stations, are connected by 1.2 m diameter vacuum tubes. At Hanford, the need to accommodate a second interferometer required doubling the number of chambers, although most of the vacuum tubes were shared by the two laser beams and only minimal additions were needed to connect the extra chambers. Each chamber was equipped with an optical table, passively isolated from seismic vibrations by a 4-stage spring-mass system, providing about 6 orders of magnitude isolation at 100 Hz[Giaime *et al.* (1996)]. Single pendulum suspensions were used to support the most critical optical components, and in particular the 10 Kg, 25 cm diameter end mirrors of the Fabry-Pérot arm cavities, referred to as the input and output test masses; for these optics, the pendulum suspensions provided further 4 orders of magnitude suppression of ground motion at 100 Hz. In Livingston, where the ground motion is significantly higher than in Hanford, an out-of-vacuum hydraulic pre-isolation system was added to contribute another factor 10 suppression between 0.1 and 10 Hz.

Before being decommissioned in 2010 to allow for the installation of the Advanced LIGO hardware, the LIGO detectors were fitted with a number of incremental upgrades[Aasi *et al.* (2015)] meant to improve the sensitivity and allow for prototyping some of the technologies needed for the next generation of instruments. The laser power was increased for 10 W to 35 W; the thermal compensation system, which had been added to the initial detectors to correct for thermal lensing effects, was further improved to better handle the higher circulating power; finally, a *DC readout* detection scheme was implemented, in which the interferometer was operated with a slight offset from the dark fringe and the gravitational wave signal was read directly as a modulation of the power on the photodiode. This required the installation of an output mode cleaner to filter out the RF control sidebands and higher-order spatial modes of the carrier light. This version of the detectors is referred to as Enhanced LIGO (eLIGO), and conducted science operations in 2009 and 2010.

The Virgo detector[Accadia *et al.* (2012)], in Italy, was based on a design similar to that of LIGO, except with 3 km Fabry-Pérot arms cavities.

The major difference in Virgo was the adoption of 7-stage, 10 m tall three dimensional suspensions, named *super-attenuators*, to isolate the input and output test masses. A 3D model fo the superattenuator is depicted in Fig. 1.1. The first stage is an inverted pendulum platform providing isolation at very low frequencies (about 30 mHz) and actuation capabilities for coarse alignment and compensation of tidal effects. From this platform hangs a chain of five cascaded single-wire pendula, each about 1 m long; the mass of each pendulum, as well as the inverted pendulum stage, integrates a mechanical filter that provides vertical isolation for the suspension point of the subsequent stage; the vertical isolation is realized by supporting the suspension point with an array of pre-curved triangular steel blades which lay flat under the load and provide a vertical resonant frequency at about 1.5 Hz. The overall vertical resonant frequency is further lowered to below 0.5 Hz by the adoption of magnetic anti-springs. The payload is comprised of the test mass and a reaction mass, an hollow cylinder concentric with the test mass used a quite reference point for actuation on the mirror. Both are suspended to a crossbar, called the *marionette*, via two loops of wire each. The marionette is equipped with actuators that allow it, and consequently the payload, to be steered with respect to the above suspension stage. The *super-attenuators* were designed to provide at least 10 orders of magnitude isolation down to 4 Hz, extending the Virgo observation band to lower frequencies compared to the other detectors of the same generation. A shorter and simplified version of the superattenuator was used to suspend optical benches for less critical optics.

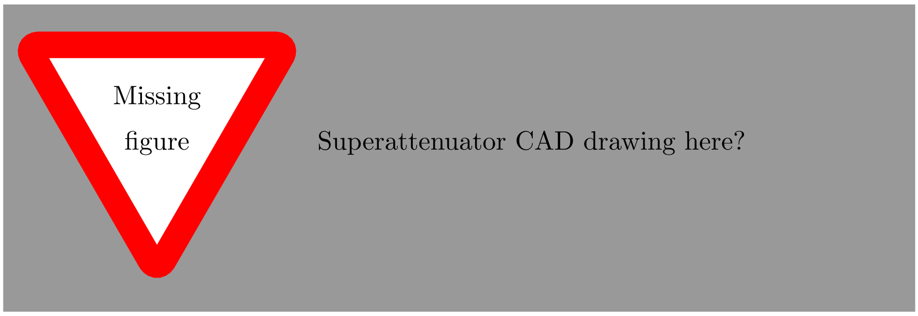

Fig. 1.1 A 3D model of the Virgo superattenuator

Similar to what was done with LIGO, Virgo was also equipped with a number of incremental upgrades aimed at improving the sensitivity and testing the maturity of technologies needed for the subsequent version of the detector. Most notably, the laser power was increased from 10 W to 25 W, a thermal compensation system was added, and the test masses were suspended using fused silica fiber directly bonded to the optics to reduce thermal noise[Lorenzini (2010)]. In this configuration, the instrument was referred to as Virgo+.

GEO600 [Grote (2010)], on the other hand, adopted quite different design choices, and pioneered a number of innovative technologies of which several would later be integrated in the larger detectors: instead of Faby-Pérot arm cavities it employed folded arms, a topology in which the end of the arms are occupied by folding mirrors that send the laser back towards the end test masses located close to the beam splitter; it was the first detector to employ a signal recycling cavity to shape the gravitational wave signal frequency response [Willke *et al.* (2002)]; it also employed DC readout, rather than the more conventional RF homodyne readout [Hild *et al.* (2009)]; it was the first detector to use monolithic final-stage suspensions of the test-masses [Plissi *et al.* (2000)]; finally, it was the first to employ squeezing, a technique used to shape quantum fluctuations and obtain a reduction in relative shot noise equivalent to that of a higher power laser [Grote *et al.* (2013)]. GEO600 was also the only observatory to remain active during the period in which LIGO and VIRGO were being upgraded to their second generation.

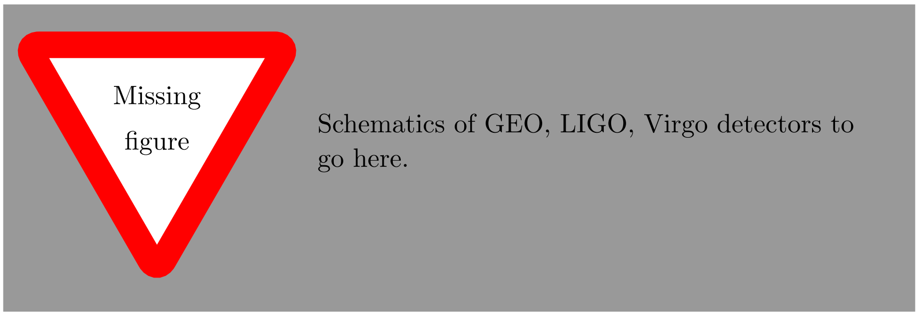

Fig. 1.2 Schematics optical layouts of GEO600, LIGO and Virgo.

TAMA300[Ando and the TAMA collaboration (2002)], in Japan, also adopted an optical layout similar to LIGO and VIRGO, although its smaller size and location in Tokyo severely limited its sensitivity below a a few hundred Hz. It was nevertheless instrumental in developing sensing and control techniques that would be later transferred to the larger interferometers. The CLIO detector, also in Japan but situated in the Kamioka mine, began construction in 2003 and was eventually operated with cryogenically cooled test masses and demonstrated a reduced thermal noise level from the room temperature [Uchiyama *et al.* (2012)]. However, with relatively short arm lengths of 100 m CLIO could not come close to the strain sensitivities of the larger detectors.

In 2002, the LIGO detectors and GEO600 reached a sensitivity adequate for collecting science data, although still far from the design goal. The first science run took place between August and September 2002 with a conventional range, intended as the maximum distance at which a standard NS-NS coalescence could be detected with a signal-to-noise ratio equal to 8, of 100 kpc, more than two orders of magnitude less than the design value of 18 Mpc. In the years that followed, LIGO conducted other 5 science runs, interrupted by commissioning periods that steadily and consistently improved the performance until it finally reached full design sensitivity in 2006. In all but one of these science runs, the three LIGO detectors were run in coincidence with one or more other large scale detectors around the world (GEO600, Virgo and TAMA300) to leverage the superior noise rejection and sky localization capabilities of a widely distributed network of detectors[Abbott *et al.* (2004, 2005, 2006, 2008); Abadie *et al.* (2010)].

1.1.3 *Design and operation of the second generation of interferometric gravitational wave detectors*

Even while the initial LIGO and Virgo detectors were still far from their design sensitivities, plans were afoot for major upgrades to each, aimed at achieving roughly a factor 10 improvement in sensitivity over the whole frequency band. This generation of detectors would be known as the 2nd generation, or the advanced detectors; Advanced LIGO and Advanced Virgo.

Besides generally targeting a factor 10 overall improvement in sensitivity, and an expansion of the sensitive frequency band towards lower frequencies, the design of the advanced detectors was aimed at making them limited by fundamental noises: thermal noise, laser radiation pressure and laser shot noise. As a consequence, all other possible sources of noise needed to be pushed well below these main ones.

1.1.3.1 *Advanced LIGO*

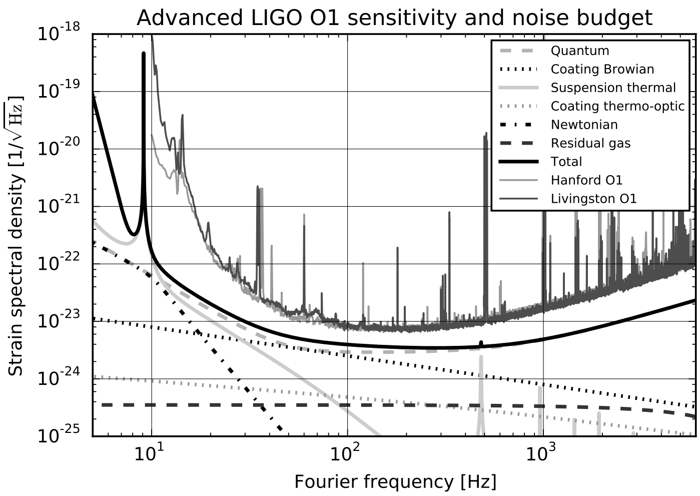

Fig. 1.3 Predicted strain equivalent spectral densities for major noise sources in Advanced LIGO in the optimal configuration. Also shown are the typical strain sensitivities of the Hanford and Livingston detectors throughout the O1 run, during which the first direct detection of gravitational waves was made.

Suspensions and seismic isolation. Two of the subsystems that were significantly upgraded from LIGO to Advanced LIGO were the Seismic Isolation[Matichard *et al.* (2015)] and Suspension subsystems. Although they are formally two separate subsystems, they work in concert to isolate the test-masses and other critical optics from ground vibrations and other macroscopic motions, and ensure that the they can move as free masses in the relevant degree of freedom above a few Hz.

In Advanced LIGO, the test masses are suspended by four-stage pendula, known as the quad suspensions[Aston *et al.* (2012)]. From top to bottom, the main suspension chain is composed of two metal masses, and two optics of the same shape and size, the lowermost one being the test mass. The first metal mass is attached to the suspension structure by four *spring blades*, which are flexible metal blades providing vertical isolation; steel wires run from the tip of the blades to the suspended mass. In a similar fashion, the second metal mass is attached to the first one, and so is the topmost optic. In the lower stage of the suspension, however, the test mass is attached to the topmost optic by four fused silica fibers; these are directly welded to the two optics in a monolithic assembly. The monolithic suspension design offers reduced mechanical losses, and consequently lower thermal noise, than the previously used metal wire supsensions. The pendulum resonances of the four stages are distributed between 1 and 4 Hz, providing a passive suppression of motion along the optical axis by 10^7 at 10 Hz, and going down as the frequency to the eighth power.

A similar chain of masses, called the reaction chain, hangs parallel to the main one, and supports the sensors and actuators used for local damping and active alignment of the lowermost three masses of the main chain; this provides a quiet reference point for the control forces. The top masses of both chains are instead actuated using the suspension structure as a reference. For all stages except the lowest, the sensors/actuators are compact units that use shadow sensors to measure the position of, and electromagnets to exert forces on, permanent magnets attached to the masses. The last stage has no local sensors, since the position of the test mass is sensed by the global interferometry; on the end test mass, the actuators consist of patterns of electrodes deposited on the last mass of the reaction chain, which exert electrostatic forces on the test mass when polarized. This avoids the need of attaching magnets to the test masses, thus maintaining low mechanical losses and reducing possible couplings to external fields. The last stage of the reaction chain on the input test mass suspension has no actuators at all, and is instead used as the compensation plate for the thermal compensation system.

Each quad suspension is attached to an in-vacuum seismic isolation platform, used for further suppression of ground vibrations and precise positioning and alignment with a larger range than allowed by the suspensions themselves. The platforms are six-axis, with two-stage active and passive isolators proving more than 3 orders of magnitude isolation above 1 Hz, and positioning capabilities with nm resolution over a range of several mm.

Similar seismic isolation platforms are used to support all the in-vacuum optics; the optics that are part of an optical cavity are further suspended by triple-pendula, while single-pendulum suspensions, or specialized geometries, are used to isolate less critical optics where necessary.

In both the Hanford and Livingston Advanced LIGO detectors, each of the in-vacuum seismic isolation platforms is installed on beams that are decoupled from the vacuum system itself via flexible bellows, and supported from the outside using hydraulic actuated piers anchored to ground. This systems acts as a further layer of isolation and is used to predictively correct for macroscopic positioning drifts caused by tidal forces from the moon and the sun.

Laser At frequencies above about 100 Hz, the interferometer sensitivity is limited by shot noise in the laser. The relative impact of the shot noise scales as the inverse of the square root of the power: increasing the laser power is thus a conceptually straightforward way of improving the sensitivity in the shot-noise limited band. The Advanced LIGO laser source is designed to deliver a maximum of 180 W of laser power, as opposed to the 35 W used in eLIGO. In order to achieve this goal the laser source is comprised of a 2 W Nd:YAG 1064 nm non-planar ring oscillator (NPRO) master laser, amplified up to 35 W by a single-pass medium-power amplifier, subsequently amplified to 220 W by an injection-locked ring ring oscillator known as the high-power oscillator stage [Kwee *et al.* (2012)].

This beam is then pre-stabilized in frequency with respect to a fixed spacer cavity in a thermally shielded environment, and pre-stabilized in intensity with respect to several reference photodiodes. The beam from the pre-stabilized laser is also passed through a pre-mode cleaner ring cavity, which filters the spatial mode of the laser ensuring a high-purity Gaussian beam profile. The beam is then handed off to the Input Optic subsystem, where first phase modulation sidebands are applied and the power of the beam is controlled, before the beam is passed to the in-vacuum suspended input mode cleaner cavity [Mueller *et al.* (2016)]. This cavity serves to further filter the beam in both frequency and spatial mode, passively suppressing any beam jitter of the pre-stabilized laser beam from non-isolated optical components. The beam transmitted from the input mode cleaner is then passed through a Faraday isolator, before being exapnded and matched to the main interferometer mode.

Thermal compensation system Despite the stringent requirement on the optical absorption of bulk and coating material of the optics, the high power levels circulating in the interferometer result in a non-negligible amount of heat released into the optics. Due to the poor heat conduction in vacuum, this induces important thermal gradients that can modify the optical parameters of the system via two main effects: thermal lensing in the bulk material due to the temperature dependence of the refractive index, and distortion of the high reflectivity (HR) surface of the mirrors due to thermo-mechanical stress. HR surface distortion is particularly important for the input and end test masses, both because of they see the highest power level of all the interferometer optics (up to about 1 MW), and because any deformation of their surface has a bigger impact on the interferometer output. Thermal lensing, while irrelevant for the end test mass due to the negligible amount of power transmitted, is an important effect in the input test masses, since it can spoil both he mode matching with the power recycling cavity and the mode overlap between the two arm cavities, thus increasing the contrast defect when the two beams interfere. The Advanced LIGO thermal compensation system is designed to monitor and compensate for both effects across the entire range of operating powers, and constitutes a substantial improvement oever the much simpler implementation used in eLIGO. To sense the thermal distortion, each of the four input and end test masses is monitored using a custom Harthman wavefront sensors, which uses an auxiliary laser beam injected from the anti-reflection face of the optic and reflected back from the HR side (thus crossing the optic twice). To correct for HR surface distortions, an infrared annular heater heats the test masses' barrel, reducing the thermal gradient and inducing a thermal stress that compensates counteracts the effect of central heating due to the main laser beam. Finally, a CO_2 laser projector is used to impress a suitable pattern on the compensation plate, deliberately creating a thermal lens that compensate that left in the input test mass by the combined effect of the science beam and the annular heater[**?**].

Optical layout The optical layout of Advanced LIGO is different from the initial LIGO layout in several ways. Probably the most fundamental change to the optical layout is the addition of a signal recycling mirror between the anti-symmetric side of the beam splitter and the optical detection port. In its current configuration this oft-called signal recycling mirror is actually tuned such as to increase the bandwidth of the detector, rather than increasing the quantum noise-limited sensitivity in a narrow band as the name *recycling* implies. As such, a more apposite name for this mirror in the current configuration is signal *extraction* mirror.

The signal extraction mirror forms a new cavity within Advanced LIGO; the signal recycling cavity. Both the signal recycling cavity and the power recycling cavity in Advanced LIGO are designed to be geometrically *stable*, by which it should be understood that the round-trip Gouy phase in the cavity is significant, and thus higher-order spatial modes are non-degenerate [Arain and Mueller (2008)]. This is contrast to the power recycling cavity in initial LIGO, which was only marginally stable. The advantages of the stable recycling cavity design have been clear during the commissioning of Advanced LIGO, where commissioning of the length and alignment sensing and control systems has been a much smoother process than in initial LIGO.

Another important geometric change to the optical layout between initial LIGO and Advanced LIGO is in the arm cavities. There was a drive towards using larger beam spot sizes on the mirrors in Advanced LIGO in order to mitigate the effects of thermal noise. In general there are two cavity geometry solutions available that will give a specific beam spot size on the mirrors for a two-mirror cavity of fixed length. The initial LIGO arm cavities were designed with a large beam waist inside the cavities whereas Advanced LIGO uses the alternative solution of having a small beam waist size in the cavities. The major advantage to the small beam waist size solution is that thermal deformations of the test masses caused by absorption in the coatings push the cavity to a more stable geometry, rather than towards a less stable geometry as is the case for the large beam waist design.

Several additional optical subsystems have been added in the upgrade from initial LIGO to Advanced LIGO. During the enhanced LIGO phase (shortly before initial LIGO went offline for the major upgrade to aLIGO) an output mode cleaner was added at the output port. The output mode cleaner is a crucial component of the DC readout scheme which was first demonstrated in GEO600, and which was determined to be a more optimal solution for readout of the gravitational wave signal than the previously used RF heterodyne readout scheme [Hild *et al.* (2009)]. The output mode cleaner subsystem was retained in the aLIGO optical layout, and takes the form of a suspended fixed spacer cavity with a bow tie configuration. The output mode cleaner has the essential function of removing RF sidebands and higher-order spatial modes from the light incident on the photodiode, thus mitigating their impact on the shot noise sensitivity.

A great effort was made in the upgrade to Advanced LIGO to make the lock acquisition process more deterministic than stochastic. Part of this effort was the inclusion of the arm length stabilization (ALS) subsystem. This subsystem uses green frequency-doubled Nd:YAG beams which are phased locked to the main laser to independently control the arm cavities during lock acquisition of the central dual-recycled Michelson interferometer (DRMI) [Staley *et al.* (2014)]. Once the DRMI is locked the ALS can be used methodically bring the arms to resonance, bringing the full interferometer to the ideal operating point.

Interferometric sensing and control The dual-recycled Fabry-Pérot Michelson interferometer that makes up aLIGO has a very narrow linear range. The practical consequence of this fact, combined with the fact that even with the advanced seismic isolation systems typical mirror motions at low frequencies can be of the order several wavelengths, is that length control loops are essential in order to keep the interferometer within the linear range.

The length sensing of all interferometric ground-based GW detectors is based on the Pound-Drever-Hall (PDH) laser frequency stabilization scheme [Drever *et al.* (1983)]. In this scheme an electro-optic modulator is used to add to the main laser frequency RF phase modulation sidebands, which are typically non-resonant in an optical cavity when the carrier light is resonant. When the carrier light frequency is brought close to resonance in the cavity, the carrier picks up a phase shift in reflection of the cavity which is proportional to the difference between carrier light frequency and the cavity resonant frequency. The sidebands act as a phase reference for comparison with the carrier light, and the reflected light from the cavity is detected with a photodetector and demodulated at the original modulation frequency to give an error signal for either the cavity length control or the laser frequency control.

While the PDH scheme described above describes the sensing of just one length (or frequency) degree of freedom, the core interferometers of 2nd generation ground-based GW detectors require 5 distinct length degrees of freedom to be sensed and controlled. Typically these degrees of freedom are broken down into the following list: common arm length, differential arm length (where the GW signal predominantly appears), Michelson tuning, power recycling cavity length and signal recycling cavity length. In reality at least two additional degrees of freedom must be controlled; one each for the input and output mode cleaner cavities. This presents a formidable challenge, which was solved for Advanced LIGO by the use of two different modulation frequencies, at roughly 9 MHz and 45 MHz. The 9 MHz sidebands are resonant in the power recycling cavity only, and experience a dark Michelson fringe. Detectors at various ports demodulated at this frequency typically provide good length sensing signals for the arm degrees of freedom, as well as the power recycling cavity length. The 45 MHz sidebands are resonant in both power and signal recycling cavities, and experience a bright Michelson fringe. As a result, the detectors demodulated at 45 MHz provide good sensitivity to signal recycling cavity length.

The alignment of optics must also be sensed and controlled in GW detectors. In aLIGO the sensing is currently achieved using a method called differential wavefront sensing, developed by Henry Ward and colleagues [Morrison *et al.* (1994a,b)]. This method is similar in principle to the PDH length sensing, except that quadrant photodectors are used instead of single-element photodetectors in order to measure the beats between sidebands and carrier in different spatial modes. An alternative method developed by Dana Anderson was used in Virgo, whereby the sideband frequencies were chosen such that higher-order spatial modes of the sidebands would be co-resonant in some of the optical cavities with the carrier fundamental mode [Anderson (1984)]. A detailed description of the alignment requirements of a gravitational wave detector, and a sensing scheme based on the wavefront sensing is provided in [Fritschel *et al.* (1998)].

1.1.3.2 *Advanced Virgo*

At the time of writing, Advanced Virgo is still in the process of installation of upgrades and commissioning. The superattenuator test-mass suspensions in Virgo already performed extremely well for suppressing the coupling of ground motion to test-mass motion, and so upgrades in this area were minimal. The laser power is being increased in order to reduce the increase the shot noise sensitivity of the detector, and new test-masses with low mechanical loss coatings are being installed. The optical layout is very similar to Advanced LIGO, being a dual-recycled Fabry-Pérot Michelson interferometer employing DC readout with an output mode cleaner. Due to restrictions in available vacuum enclosure space, however, stable recycling cavities were not a feasible design option for Advanced Virgo.

1.1.4 *The future of ground based interferometric gravitational wave detection*

After the announcement of the first detection of gravitational waves by the LIGO-Virgo collaboration, the anticipation for an extended network of detectors to come online became even more pressing. Now that the possibility of detecting gravitational waves had been proven, the scientific community was looking forward to the science that can be done by collecting and analyzing a large number of events with well constrained parameters. A network of three or more detectors would improve on a number of key factors, including the coincident duty cycle, better parameter estimation and much more precise sky localization. The latter is fundamental to increase the odd of simultaneously observing an event in both the GW and EM spectra, thus enabling the so called *multi-messenger astronomy*.

Virgo was already expected to join the second LIGO observing run starting in summer 2016, and despite some installation and commissioning issues, the LIGO and Virgo communities are working hard to make it happen.

It was not originally planned for Kagra to join the network with meaningful sensitivity before 2018, and various delays are pushing the schedule back even more. The managing team went trough a redefinition of the schedule in winter 2016, and outlined a plan to skip an intermediate commissioning phase and accelerate the path to the final, cryogenic version of the detector. In spring 2016 the interferometer was locked for the first time in a simple Michelson configuration with no arm cavities or recycling cavities, but using the full 3 km arm-length.

The announcement of the detection of GW150914 also gave a decisive impulse to the LIGO India project. As for Initial LIGO, the Advanced LIGO project included two interferometers to be installed in the Hanford site vacuum system. Unlike for Initial LIGO, the second interferometer was designed to be 4 km long, rather than 2 km. Shortly after the installation phase began, an idea started to take hold in the community: what if, instead of building two co-located interferometers that would be affected by the same disturbances and not add much to the science output, the third instrument could be moved to a completely different location? If a country was willing to invest in the construction of the infrastructure and vacuum system, it would be rewarded with the ability to jump to the forefront of gravitational wave science by borrowing from the Advanced LIGO project all the instrumentation that was designed and built for the second Hanford detector. Besides likely improving the overall network duty cycle, a strategic placement of the additional detector would also greatly improve the parameter estimation and localization capability of the network [Klimenko *et al.* (2016)]. Australia was initially identified as a possible partner; when funding constraints made it clear that the deal could not happen on fruitful time scales, India stepped in. The project seemed to move quickly at the beginning, with the INDIGO (the Indian gravitational wave community) management putting forward a great effort to train their scientists, complete site surveys and make all other necessary preparations, with great help and support by the LIGO management. Unfortunately, a change in government slowed process almost to a halt in 2015. It was only after the announcement of the first discovery by the LIGO project that the Indian government approved the project. Although the detector is not projected to come online before 2022, this represents an important success that will strategically expand the network of GW detectors and the list of countries involved.

In the meanwhile, the LIGO project is already researching possible upgrades, to be developed and installed in a few years time-frame in the current detectors without the need of a complete rebuild. Such upgrades includes frequency dependent squeezing, heavier test masses, improved coating, suspensions with reduced thermal noise and strategies to subtract Newtonian noise. Proposals are also being considered to cool down the test masses, thus reducing thermal noise in coating and suspensions.

Despite the factor of few improvement in overall sensitivity attainable with the above mentioned upgrades, the GW community is starting to realize that a substantial gains in maximum and low-frequency sensitivity will require to abandon the current infrastructures. Different studies are being carried out to shape the concept of the next generation of ground detector, including a proposal in the LIGO community to move to a detector of essentially the same design, but substantially increased length [Dwyer *et al.* (2015)]. The most advanced and well studied concept, however, has been developed by the European community for a detector dubbed Einstein Telescope [Punturo and et al. (2010)]. The observatory would be built about 150 m underground, in a system of galleries forming a 10 km side horizontal equilateral triangle. Three detectors would be co-located in the facility, with each vertex of the triangle hosting the corner station of one, and the end stations of other two. Each detector would actually be comprised of two dual-recycled, Fabry-Pérot Michelson interferometers, sharing the same geometrical arrangement but optimized for two different frequencies bands: a cryogenic, low power one for the lower frequency sensitivity, and a room temperature more powerful version for higher frequency sensitivity.

Compared to any one of the current observatories, the six interferometers combined would exhibit a much more uniform antenna pattern, in terms of both sky-position and polarization of the sources, improve the maximum sensitivity by more than a factor of 10 and allow to observe signals down to about 1 Hz. Their proposed design is based on technologies that are currently state of the art, or have a mature enough state of development to make solid prediction about their future performance possible; however, the ET community has made clear that one of the main goal of the proposal is that of building an infrastructure for an observatory expected to remain current for decades, while the hosted instrumentation is upgraded according to the latest developments.

The nature of the field of gravitational wave detection is such that it may be many years before a new breakthrough technology with the power to improve the strain sensitivity makes it from the conceptual stage to real implementation in a full scale detector. As such, research groups around the world are already working hard on developing the technologies of the future, perhaps a decade or more before they might make it into the vacuum enclosures and clean rooms of the future instruments. This constant drive for better sensitivity makes the field a very creative one, and one in which there can be expected to be many years of innovation and technical achievements still to come, even after the first direct detection of gravitational waves.

Bibliography

Aasi, J., Abadie, J., Abbott, B. P., Abbott, R., Abbott, T., Abernathy, M. R., Accadia, T., Acernese, F., Adams, C., Adams, T., Adhikari, R. X., Affeldt, C., Agathos, M., Aggarwal, N., Aguiar, O. D., Ajith, P., Allen, B., Allocca, A., Ceron, E. A., Amariutei, D., Anderson, R. A., Anderson, S. B., Anderson, W. G., Arai, K., Araya, M. C., Arceneaux, C., Areeda, J., Ast, S., Aston, S. M., Astone, P., Aufmuth, P., Aulbert, C., Austin, L., Aylott, B. E., Babak, S., Baker, P. T., Ballardin, G., Ballmer, S. W., Barayoga, J. C., Barker, D., Barnum, S. H., Barone, F., Barr, B., Barsotti, L., Barsuglia, M., Barton, M. A., Bartos, I., Bassiri, R., Basti, A., Batch, J., Bauchrowitz, J., Bauer, T. S., Bebronne, M., Behnke, B., Bejger, M., Beker, M. G., Bell, A. S., Bell, C., Belopolski, I., Bergmann, G., Berliner, J. M., Bertolini, A., Bessis, D., Betzwieser, J., Beyersdorf, P. T., Bhadbhade, T., Bilenko, I. A., Billingsley, G., Birch, J., Bitossi, M., Bizouard, M. A., Black, E., Blackburn, J. K., Blackburn, L., Blair, D., Blom, M., Bock, O., Bodiya, T. P., Boer, M., Bogan, C., Bond, C., Bondu, F., Bonelli, L., Bonnand, R., Bork, R., Born, M., Bose, S., Bosi, L., Bowers, J., Bradaschia, C., Brady, P. R., Braginsky, V. B., Branchesi, M., Brannen, C. A., Brau, J. E., Breyer, J., Briant, T., Bridges, D. O., Brillet, A., Brinkmann, M., Brisson, V., Britzger, M., Brooks, A. F., Brown, D. A., Brown, D. D., Brckner, F., Bulik, T., Bulten, H. J., Buonanno, A., Buskulic, D., Buy, C., Byer, R. L., Cadonati, L., Cagnoli, G., Bustillo, J. C., Calloni, E., Camp, J. B., Campsie, P., Cannon, K. C., Canuel, B., Cao, J., Capano, C. D., Carbognani, F., Carbone, L., Caride, S., Castiglia, A., Caudill, S., Cavagliá, M., Cavalier, F., Cavalieri, R., Cella, G., Cepeda, C., Cesarini, E., Chakraborty, R., Chalermsongsak, T., Chao, S., Charlton, P., Chassande-Mottin, E., Chen, X., Chen, Y., Chincarini, A., Chiummo, A., Cho, H. S., Chow, J., Christensen, N., Chu, Q., Chua, S. S. Y., Chung, S., Ciani, G., Clara, F., Clark, D. E., Clark, J. A., Cleva, F., Coccia, E., Cohadon, P.-F., Colla, A., Colombini, M., Jr, M. C., Conte, A., Conte, R., Cook, D., Corbitt, T. R., Cordier, M., Cornish, N., Corsi, A., Costa, C. A., Coughlin, M. W., Coulon, J.-P., Countryman, S., Couvares, P., Coward, D. M., Cowart, M., Coyne, D. C., Craig, K., Creighton, J. D. E., Creighton, T. D., Crowder, S. G., Cumming, A., Cunningham, L., Cuoco, E., Dahl, K., Canton, T. D., Damjanic, M., Danilishin, S. L., D'Antonio, S., Danzmann, K., Dattilo, V., Daudert, B., Daveloza, H., Davier, M., Davies, G. S., Daw, E. J., Day, R., Dayanga, T., Debreczeni, G., Degallaix, J., Deleeuw, E., Deléglise, S., Pozzo, W. D., Denker, T., Dent, T., Dereli, H., Dergachev, V., Rosa, R. D., DeRosa, R. T., DeSalvo, R., Dhurandhar, S., az, M. D., Dietz, A., Fiore, L. D., Lieto, A. D., Palma, I. D., Virgilio, A. D., Dmitry, K., Donovan, F., Dooley, K. L., Doravari, S., Drago, M., Drever, R. W. P., Driggers, J. C., Du, Z., Dumas, J.-C., Dwyer, S., Eberle, T., Edwards, M., Effler, A., Ehrens, P., Eichholz, J., Eikenberry, S. S., Endrczi, G., Essick, R., Etzel, T., Evans, K., Evans, M., Evans, T., Factourovich, M., Fafone, V., Fairhurst, S., Fang, Q., Farr, B., Farr, W., Favata, M., Fazi, D., Fehrmann, H., Feldbaum, D., Ferrante, I., Ferrini, F., Fidecaro, F., Finn, L. S., Fiori, I., Fisher, R., Flaminio, R., Foley, E., Foley, S., Forsi, E., Forte, L. A., Fotopoulos, N., Fournier, J.-D., Franco, S., Frasca, S., Frasconi, F., Frede, M., Frei, M., Frei, Z., Freise, A., Frey, R., Fricke, T. T., Fritschel, P., Frolov, V. V., Fujimoto, M.-K., Fulda, P., Fyffe, M., Gair, J., Gammaitoni, L., Garcia, J., Garufi, F., Gehrels, N., Gemme, G., Genin, E., Gennai, A., Gergely, L., Ghosh, S., Giaime, J. A., Giampanis, S., Giardina, K. D., Giazotto, A., Gil-Casanova, S., Gill, C., Gleason, J., Goetz, E., Goetz, R., Gondan, L., González, G., Gordon, N., Gorodetsky, M. L., Gossan, S., Goßler, S., Gouaty, R., Graef, C., Graff, P. B., Granata, M., Grant, A., Gras, S., Gray, C., Greenhalgh, R. J. S., Gretarsson, A. M., Griffo, C., Grote, H., Grover, K., Grunewald, S., Guidi, G. M., Guido, C., Gushwa, K. E., Gustafson, E. K., Gustafson, R., Hall, B., Hall, E., Hammer, D., Hammond, G., Hanke, M., Hanks, J., Hanna, C., Hanson, J., Harms, J., Harry, G. M., Harry, I. W., Harstad, E. D., Hartman, M. T., Haughian, K., Hayama, K., Heefner, J., Heidmann, A., Heintze, M., Heitmann, H., Hello, P., Hemming, G., Hendry, M., Heng, I. S., Heptonstall, A. W., Heurs, M., Hild, S., Hoak, D., Hodge, K. A., Holt, K., Hong, T., Hooper, S., Horrom, T., Hosken, D. J., Hough, J., Howell, E. J., Hu, Y., Hua, Z., Huang, V., Huerta, E. A., Hughey, B., Husa, S., Huttner, S. H., Huynh, M., Huynh-Dinh, T., Iafrate, J., Ingram, D. R., Inta, R., Isogai, T., Ivanov, A., Iyer, B. R., Izumi, K., Jacobson, M., James, E., Jang, H., Jang, Y. J., Jaranowski, P., Jiménez-Forteza, F., Johnson, W. W., Jones, D., Jones, D. I., Jones, R., (2015). Characterization of the LIGO detectors during their sixth science run, *Class. Quantum Grav.* **32**, 11, p. 115012, doi:10.1088/0264-9381/32/11/115012, `http://dx.doi.org/10.1088/0264-9381/32/11/115012`.

Abadie, J., Abbott, B. P., Abbott, R., Accadia, T., Acernese, F., Adhikari, R., Ajith, P., Allen, B., Allen, G., Ceron, E. A., Amin, R. S., Anderson, S. B., Anderson, W. G., Antonucci, F., Arain, M. A., Araya, M., Arun, K. G., Aso, Y., Aston, S., Astone, P., Aufmuth, P., Aulbert, C., Babak, S., Baker, P., Ballardin, G., Ballmer, S., Barker, D., Barone, F., Barr, B., Barriga, P., Barsotti, L., Barsuglia, M., Barton, M. A., Bartos, I., Bassiri, R., Bastarrika, M., Bauer, T. S., Behnke, B., Beker, M. G., Belletoile, A., Benacquista, M., Betzwieser, J., Beyersdorf, P. T., Bigotta, S., Bilenko, I. A., Billingsley, G., Birindelli, S., Biswas, R., Bizouard, M. A., Black, E., Blackburn, J. K., Blackburn, L., Blair, D., Bland, B., Blom, M., Boccara, C., Bock, O., Bodiya, T. P., Bondarescu, R., Bondu, F., Bonelli, L., Bonnand, R., Bork, R., Born, M., Bose, S., Bosi, L., Bouhou, B., Braccini, S., Bradaschia, C., Brady, P. R., Braginsky, V. B., Brau, J. E., Breyer, J., Bridges, D. O., Brillet, A., Brinkmann, M., Brisson, V., Britzger, M., Brooks, A. F., Brown, D. A., Budzyński, R., Bulik, T., Bullington, A., Bulten, H. J., Buonanno, A., Burmeister, O., Buskulic, D., Buy, C., Byer, R. L., Cadonati, L., Cagnoli, G., Cain, J., Calloni, E., Camp, J. B., Campagna, E., Cannizzo, J., Cannon, K. C., Canuel, B., Cao, J., Capano, C. D., Carbognani, F., Cardenas, L., Caudill, S., Cavaglià, M., Cavalier, F., Cavalieri, R., Cella, G., Cepeda, C., Cesarini, E., Chalermsongsak, T., Chalkley, E., Charlton, P., Chassande-Mottin, E., Chatterji, S., Chelkowski, S., Chen, Y., Chincarini, A., Christensen, N., Chua, S. S. Y., Chung, C. T. Y., Clark, D., Clark, J., Clayton, J. H., Cleva, F., Coccia, E., Colacino, C. N., Colas, J., Colla, A., Colombini, M., Conte, R., Cook, D., Corbitt, T. R. C., Cornish, N., Corsi, A., Coulon, J.-P., Coward, D., Coyne, D. C., Creighton, J. D. E., Creighton, T. D., Cruise, A. M., Culter, R. M., Cumming, A., Cunningham, L., Cuoco, E., Dahl, K., Danilishin, S. L., D'Antonio, S., Danzmann, K., Dattilo, V., Daudert, B., Davier, M., Davies, G., Daw, E. J., Day, R., Dayanga, T., Rosa, R. D., DeBra, D., Degallaix, J., del Prete, M., Dergachev, V., DeSalvo, R., Dhurandhar, S., Fiore, L. D., Lieto, A. D., Emilio, M. D. P., Virgilio, A. D., Díaz, M., Dietz, A., Donovan, F., Dooley, K. L., Doomes, E. E., Drago, M., Drever, R. W. P., Driggers, J., Dueck, J., Duke, I., Dumas, J.-C., Dwyer, S., Edgar, M., Edwards, M., Effler, A., Ehrens, P., Etzel, T., Evans, M., Evans, T., Fafone, V., Fairhurst, S., Faltas, Y., Fan, Y., Fazi, D., Fehrmann, H., Ferrante, I., Fidecaro, F., Finn, L. S., Fiori, I., Flaminio, R., Flasch, K., Foley, S., Forrest, C., Fotopoulos, N., Fournier, J.-D., Franc, J., Frasca, S., Frasconi, F., Frede, M., Frei, M., Frei, Z., Freise, A., Frey, R., Fricke, T. T., Friedrich, D., Fritschel, P., Frolov, V. V., Fulda, P., Fyffe, M., Galimberti, M., Gammaitoni, L., Garofoli, J. A., Garufi, F., Gemme, G., Genin, E., Gennai, A., Ghosh, S., Giaime, J. A., Giampanis, S., Giardina, K. D., Giazotto, A., Goetz, E., Goggin, L. M., González, G., Goßler, S., Gouaty, R., Granata, M., Grant, A., Gras, S., Gray, C., Greenhalgh, R. J. S., Gretarsson, A. M., Greverie, C., Grosso, R., Grote, H., Grunewald, S., Guidi, G. M., Gustafson, E. K., Gustafson, R., Hage, B., Hallam, J. M., Hammer, D., Hammond, G. D., Hanna, C., Hanson, J., Harms, J., Harry, G. M., Harry, I. W., Harstad, E. D., Haughian, K., Hayama, K., Hayau, J.-F., Hayler, T., Heefner, J., Heitmann, H., Hello, P., Heng, I. S., Heptonstall, A., Hewitson, M., Hild, S., Hirose, E., Hoak, D., Hodge, K. A., Holt, K., Hosken, D. J., Hough, J., Howell, E., Hoyland, D., Huet, D., Hughey, B., Husa, S., Huttner, S. H., Ingram, D. R., Isogai, T., Ivanov, A., Jaranowski, P., Johnson, W. W., Jones, D. I., Jones, G., Jones, R., Ju, L., Kalmus, P., Kalogera, V., Kandhasamy, S., Kanner, J., Katsavounidis, E., Kawabe, K., Kawamura, S., Kawazoe, F., Kells, W., Keppel, D. G., Khalaidovski, A., Khalili, F. Y., Khan, R., Khazanov, E., Kim, H., King, P. J., Kissel, J. S., Klimenko, S., Kokeyama, K., Kondrashov, V., Kopparapu, R., Koranda, S., Kowalska, I., Kozak, D., Kringel, V., Krishnan, B., Królak, A., Kuehn, G., Kullman, J., Kumar, R., Kwee, P., Lam, P. K., Landry, M., Lang, M., Lantz, B., Lastzka, N., Lazzarini, A., Leaci, P., Lei, M., Leindecker, N., Leonor, I., Leroy, N., Letendre, N., Li, T. G. F., Lin, H., Lindquist, P. E., Littenberg, T. B., Lockerbie, N. A., Lodhia, D., Lorenzini, M., Loriette, V., Lormand, M., Losurdo, G., Lu, P., Lubinski, M., Lucianetti, A., Lck, H., Lundgren, A., Machenschalk, B., MacInnis, M., Mageswaran, M., Mailand, K., Majorana, E., Mak, C., Maksimovic, I., Man, N., Mandel, I., Mandic, V., Mantovani, M., Marchesoni, F., Marion, F., Márka, S., Márka, Z., Markosyan, A., Markowitz, J., Maros, E., Marque, J., Martelli, F., Martin, I. W., Martin, R. M., Marx, J. N., Mason, K., Masserot, A., Matichard, F., Maton (2010). All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-virgo run, *Physical Review D* **81**, 10, doi:10.1103/physrevd.81.102001, `http://dx.doi.org/10.1103/PhysRevD.81.102001`.

Abbott, B., Abbott, R., Adhikari, R., Ageev, A., Agresti, J., Ajith, P., Allen, B., Allen, J., Amin, R., Anderson, S. B., Anderson, W. G., Araya, M., Armandula, H., Ashley, M., Asiri, F., Aufmuth, P., Aulbert, C., Babak, S., Balasubramanian, R., Ballmer, S., Barish, B. C., Barker, C., Barker, D., Barnes, M., Barr, B., Barton, M. A., Bayer, K., Beausoleil, R., Belczynski, K., Bennett, R., Berukoff, S. J., Betzwieser, J., Bhawal, B., Bilenko, I. A., Billingsley, G., Black, E., Blackburn, K., Blackburn, L., Bland, B., Bochner, B., Bogue, L., Bork, R., Bose, S., Brady, P. R., Braginsky, V. B., Brau, J. E., Brown, D. A., Bullington, A., Bunkowski, A., Buonanno, A., Burgess, R., Busby, D., Butler, W. E., Byer, R. L., Cadonati, L., Cagnoli, G., Camp, J. B., Cannizzo, J., Cannon, K., Cantley, C. A., Cao, J., Cardenas, L., Carter, K., Casey, M. M., Castiglione, J., Chandler, A., Chapsky, J., Charlton, P., Chatterji, S., Chelkowski, S., Chen, Y., Chickarmane, V., Chin, D., Christensen, N., Churches, D., Cokelaer, T., Colacino, C., Coldwell, R., Coles, M., Cook, D., Corbitt, T., Coyne, D., Creighton, J. D. E., Creighton, T. D., Crooks, D. R. M., Csatorday, P., Cusack, B. J., Cutler, C., Dalrymple, J., D'Ambrosio, E., Danzmann, K., Davies, G., Daw, E., DeBra, D., Delker, T., Dergachev, V., Desai, S., DeSalvo, R., Dhurandhar, S., Credico, A. D., Díaz, M., Ding, H., Drever, R. W. P., Dupuis, R. J., Edlund, J. A., Ehrens, P., Elliffe, E. J., Etzel, T., Evans, M., Evans, T., Fairhurst, S., Fallnich, C., Farnham, D., Fejer, M. M., Findley, T., Fine, M., Finn, L. S., Franzen, K. Y., Freise, A., Frey, R., Fritschel, P., Frolov, V. V., Fyffe, M., Ganezer, K. S., Garofoli, J., Giaime, J. A., Gillespie, A., Goda, K., Goggin, L., González, G., Goßler, S., Grandclément, P., Grant, A., Gray, C., Gretarsson, A. M., Grimmett, D., Grote, H., Grunewald, S., Guenther, M., Gustafson, E., Gustafson, R., Hamilton, W. O., Hammond, M., Hanna, C., Hanson, J., Hardham, C., Harms, J., Harry, G., Hartunian, A., Heefner, J., Hefetz, Y., Heinzel, G., Heng, I. S., Hennessy, M., Hepler, N., Heptonstall, A., Heurs, M., Hewitson, M., Hild, S., Hindman, N., Hoang, P., Hough, J., Hrynevych, M., Hua, W., Ito, M., Itoh, Y., Ivanov, A., Jennrich, O., Johnson, B., Johnson, W. W., Johnston, W. R., Jones, D. I., Jones, G., Jones, L., Jungwirth, D., Kalogera, V., Katsavounidis, E., Kawabe, K., Kells, W., Kern, J., Khan, A., Killbourn, S., Killow, C. J., Kim, C., King, C., King, P., Klimenko, S., Koranda, S., Ktter, K., Kovalik, J., Kozak, D., Krishnan, B., Landry, M., Langdale, J., Lantz, B., Lawrence, R., Lazzarini, A., Lei, M., Leonor, I., Libbrecht, K., Libson, A., Lindquist, P., Liu, S., Logan, J., Lormand, M., Lubinski, M., Lck, H., Luna, M., Lyons, T. T., Machenschalk, B., MacInnis, M., Mageswaran, M., Mailand, K., Majid, W., Malec, M., Mandic, V., Mann, F., Marin, A., Márka, S., Maros, E., Mason, J., Mason, K., Matherny, O., Matone, L., Mavalvala, N., McCarthy, R., McClelland, D. E., McHugh, M., McNabb, J. W. C., Melissinos, A., Mendell, G., Mercer, R. A., Meshkov, S., Messaritaki, E., Messenger, C., Mikhailov, E., Mitra, S., Mitrofanov, V. P., Mitselmakher, G., Mittleman, R., Miyakawa, O., Mohanty, S., Moreno, G., Mossavi, K., Mueller, G., Mukherjee, S., Murray, P., Myers, E., Myers, J., Nagano, S., Nash, T., Nayak, R., Newton, G., Nocera, F., Noel, J. S., Nutzman, P., Olson, T., O'Reilly, B., Ottaway, D. J., Ottewill, A., Ouimette, D., Overmier, H., Owen, B. J., Pan, Y., Papa, M. A., Parameshwaraiah, V., Parameswariah, C., Pedraza, M., Penn, S., Pitkin, M., Plissi, M., Prix, R., Quetschke, V., Raab, F., Radkins, H., Rahkola, R., Rakhmanov, M., Rao, S. R., Rawlins, K., Ray-Majumder, S., Re, V., Redding, D., Regehr, M. W., Regimbau, T., Reid, S., Reilly, K. T., Reithmaier, K., Reitze, D. H., Richman, S., Riesen, R., Riles, K., Rivera, B., Rizzi, A., Robertson, D. I., Robertson, N. A., Robinson, C., Robison, L., Roddy, S., Rodriguez, A., Rollins, J., Romano, J. D., Romie, J., Rong, H., Rose, D., Rotthoff, E., Rowan, S., Rdiger, A., Ruet, L., Russell, P., Ryan, K., Salzman, I., Sandberg, V., Sanders, G. H., Sannibale, V., Sarin, P., Sathyaprakash, B., Saulson, P. R., Savage, R., Sazonov, A., Schilling, R., Schlaufman, K., Schmidt, V., Schnabel, R., Schofield, R., Schutz, B. F., Schwinberg, P., Scott, S. M., Seader, S. E., Searle, A. C., Sears, B., Seel, S., Seifert, F., Sellers, D., Sengupta, A. S., Shapiro, C. A., Shawhan, P., Shoemaker, D. H., Shu, Q. Z., Sibley, A., Siemens, X., Sievers, L., Sigg, D., Sintes, A. M., Smith, J. R., Smith, M., Smith, M. R., Sneddon, P. H., Spero, R., Spjeld, O., Stapfer, G., Steussy, D., Strain, K. A., Strom, D., Stuver, A., Summerscales, T., Sumner, M. C., Sung, M., Sutton, P. J., Sylvestre, J., Tanner, D. B., Tariq, H., Tarallo, M., Taylor, I., Taylor, R., Taylor, R., Thorne, K. A., Thorne, K. S., Tibbits, M., Tilav, S., Tinto, M., Tokmakov, K. V., Torres, C., Torrie, C., Traylor, G., (2005). Upper limits from the LIGO and TAMA detectors on the rate of gravitational-wave bursts, *Physical Review D* **72**, 12, doi:10.1103/physrevd.72.122004, `http://dx.doi.org/10.1103/PhysRevD.72.122004`.

Abbott, B., Abbott, R., Adhikari, R., Ageev, A., Allen, B., Amin, R., Anderson, S., Anderson, W., Araya, M., Armandula, H., Asiri, F., Aufmuth, P., Aulbert, C., Babak, S., Balasubramanian, R., Ballmer, S., Barish, B., Barker, D., Barker-Patton, C., Barnes, M., Barr, B., Barton, M., Bayer, K., Beausoleil, R., Belczynski, K., Bennett, R., Berukoff, S., Betzwieser, J., Bhawal, B., Bilenko, I., Billingsley, G., Black, E., Blackburn, K., Bland-

Weaver, B., Bochner, B., Bogue, L., Bork, R., Bose, S., Brady, P., Braginsky, V., Brau, J., Brown, D., Brozek, S., Bullington, A., Buonanno, A., Burgess, R., Busby, D., Butler, W., Byer, R., Cadonati, L., Cagnoli, G., Camp, J., Cantley, C., Cardenas, L., Carter, K., Casey, M., Castiglione, J., Chandler, A., Chapsky, J., Charlton, P., Chatterji, S., Chen, Y., Chickarmane, V., Chin, D., Christensen, N., Churches, D., Colacino, C., Coldwell, R., Coles, M., Cook, D., Corbitt, T., Coyne, D., Creighton, J., Creighton, T., Crooks, D., Csatorday, P., Cusack, B., Cutler, C., D'Ambrosio, E., Danzmann, K., Davies, R., Daw, E., DeBra, D., Delker, T., DeSalvo, R., Dhurandar, S., Daz, M., Ding, H., Drever, R., Dupuis, R., Ebeling, C., Edlund, J., Ehrens, P., Elliffe, E., Etzel, T., Evans, M., Evans, T., Fallnich, C., Farnham, D., Fejer, M., Fine, M., Finn, L., Flanagan, ., Freise, A., Frey, R., Fritschel, P., Frolov, V., Fyffe, M., Ganezer, K., Giaime, J., Gillespie, A., Goda, K., Gonzlez, G., Goler, S., Grandclment, P., Grant, A., Gray, C., Gretarsson, A., Grimmett, D., Grote, H., Grunewald, S., Guenther, M., Gustafson, E., Gustafson, R., Hamilton, W., Hammond, M., Hanson, J., Hardham, C., Harry, G., Hartunian, A., Heefner, J., Hefetz, Y., Heinzel, G., Heng, I., Hennessy, M., Hepler, N., Heptonstall, A., Heurs, M., Hewitson, M., Hindman, N., Hoang, P., Hough, J., Hrynevych, M., Hua, W., Ingley, R., Ito, M., Itoh, Y., Ivanov, A., Jennrich, O., Johnson, W., Johnston, W., Jones, L., Jungwirth, D., Kalogera, V., Katsavounidis, E., Kawabe, K., Kawamura, S., Kells, W., Kern, J., Khan, A., Killbourn, S., Killow, C., Kim, C., King, C., King, P., Klimenko, S., Kloevekorn, P., Koranda, S., Ktter, K., Kovalik, J., Kozak, D., Krishnan, B., Landry, M., Langdale, J., Lantz, B., Lawrence, R., Lazzarini, A., Lei, M., Leonhardt, V., Leonor, I., Libbrecht, K., Lindquist, P., Liu, S., Logan, J., Lormand, M., Lubinski, M., Lck, H., Lyons, T., Machenschalk, B., MacInnis, M., Mageswaran, M., Mailand, K., Majid, W., Malec, M., Mann, F., Marin, A., Mrka, S., Maros, E., Mason, J., Mason, K., Matherny, O., Matone, L., Mavalvala, N., McCarthy, R., McClelland, D., McHugh, M., McNamara, P., Mendell, G., Meshkov, S., Messenger, C., Mitrofanov, V., Mitselmakher, G., Mittleman, R., Miyakawa, O., Miyoki, S., Mohanty, S., Moreno, G., Mossavi, K., Mours, B., Mueller, G., Mukherjee, S., Myers, J., Nagano, S., Nash, T., Naundorf, H., Nayak, R., Newton, G., Nocera, F., Nutzman, P., Olson, T., O'Reilly, B., Ottaway, D. J., Ottewill, A., Ouimette, D., Overmier, H., Owen, B., Papa, M., Parameswariah, C., Parameswariah, V., Pedraza, M., Penn, S., Pitkin, M., Plissi, M., Pratt, M., Quetschke, V., Raab, F., Radkins, H., Rahkola, R., Rakhmanov, M., Rao, S., Redding, D., Regehr, M., Regimbau, T., Reilly, K., Reithmaier, K., Reitze, D., Richman, S., Riesen, R., Riles, K., Rizzi, A., Robertson, D., Robertson, N., Robison, L., Roddy, S., Rollins, J., Romano, J., Romie, J., Rong, H., Rose, D., Rotthoff, E., Rowan, S., Rdiger, A., Russell, P., Ryan, K., Salzman, I., Sanders, G., Sannibale, V., Sathyaprakash, B., Saulson, P., Savage, R., Sazonov, A., Schilling, R., Schlaufman, K., Schmidt, V., Schofield, R., Schrempel, M., Schutz, B., Schwinberg, P., Scott, S., Searle, A., Sears, B., Seel, S., Sengupta, A., Shapiro, C., Shawhan, P., Shoemaker, D., Shu, Q., Sibley, A., Siemens, X., Sievers, L., Sigg, D., Sintes, A., Skeldon, K., Smith, J., Smith, M., Smith, M., Sneddon, P., Spero, R., Stapfer, G., Strain, K., Strom, D., Stuver, A., Summerscales, T., Sumner, M., Sutton, P., Sylvestre, J., Takamori, A., Tanner, D., Tariq, H., Taylor, I., Taylor, R., Thorne, K., Tibbits, M., Tilav, S., Tinto, M., Tokmakov, K., Torres, C., Torrie, C., Traeger, S., Traylor, G., Tyler, W., Ugolini, D., Vallisneri, M., van Putten, M., Vass, S., Vecchio, A., Vorvick, C., Vyatchanin, S., Wallace, L., Walther, H., Ward, H., Ware, B., Watts, K., Webber, D., Weidner, A., Weiland, U., Weinstein, A., Weiss, R., Welling, H., Wen, L., Wen, S., Whelan, J., Whitcomb, S., Whiting, B., Willems, P., Williams, P., Williams, R., Willke, B., Wilson, A., Winjum, B., Winkler, W., Wise, S., Wiseman, A., Woan, G., Wooley, R., Worden, J., Yakushin, I., Yamamoto, H., Yoshida, S., Zawischa, I., Zhang, L., Zotov, N., Zucker, M., and Zweizig, J. (2004). Detector description and performance for the first coincidence observations between {LIGO} and {GEO}, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **517**, 13, pp. 154 – 179, doi:http://dx.doi.org/10.1016/j.nima.2003.11.124, `http://www.sciencedirect.com/science/article/pii/S0168900203028675`.

Abbott, B., Abbott, R., Adhikari, R., Agresti, J., Ajith, P., Allen, B., Allen, J., Amin, R., Anderson, S. B., Anderson, W. G., Araya, M., Armandula, H., Ashley, M., Aulbert, C., Babak, S., Balasubramanian, R., Ballmer, S., Bantilan, H., Barish, B. C., Barker, C., Barker, D., Barton, M. A., Bayer, K., Belczynski, K., Betzwieser, J., Bhawal, B., Bilenko, I. A., Billingsley, G., Black, E., Blackburn, K., Blackburn, L., Bland, B., Bogue, L., Bork, R., Bose, S., Brady, P. R., Braginsky, V. B., Brau, J. E., Brown, D. A., Buonanno, A., Busby, D., Butler, W. E., Cadonati, L., Cagnoli, G., Camp, J. B., Cannizzo, J., Cannon, K., Cao, J., Cardenas, L., Carter, K., Casey, M. M., Charlton, P., Chatterji, S., Chen, Y., Chin, D., Christensen, N., Cokelaer, T., Colacino, C. N., Coldwell, R., Cook, D., Corbitt, T., Coyne, D., Creighton, J. D. E., Creighton, T. D., Dalrymple, J., D'Ambrosio, E., Danzmann, K., Davies, G., DeBra, D., Dergachev, V., Desai, S., DeSalvo, R., Dhurandar, S., Díaz, M., Credico, A. D., Drever, R. W. P., Dupuis, R. J., Ehrens, P., Etzel, T., Evans, M., Evans, T., Fairhurst, S., Finn, L. S., Franzen, K. Y., Frey, R. E., Fritschel, P., Frolov, V. V., Fyffe, M., Ganezer, K. S., Garofoli, J., Gholami, I., Giaime, J. A., Goda, K., Goggin, L., González, G., Gray, C., Gretarsson, A. M., Grimmett, D., Grote, H., Grunewald, S., Guenther, M., Gustafson, R., Hamilton, W. O., Hanna, C., Hanson, J., Hardham, C., Harry, G., Heefner, J., Heng, I. S., Hewitson, M., Hindman, N., Hoang, P., Hough, J., Hua, W., Ito, M., Itoh, Y., Ivanov, A., Johnson, B., Johnson, W. W., Jones, D. I., Jones, G., Jones, L., Kalogera, V., Katsavounidis, E., Kawabe, K., Kawamura, S., Kells, W., Khan, A., Kim, C., King, P., Klimenko, S., Koranda, S., Kozak, D., Krishnan, B., Landry, M., Lantz, B., Lazzarini, A., Lei, M., Leonor, I., Libbrecht, K., Lindquist, P., Liu, S., Lormand, M., Lubinski, M., Lck, H., Luna, M., Machenschalk, B., MacInnis, M., Mageswaran, M., Mailand, K., Malec, M., Mandic, V., Márka, S., Maros, E., Mason, K., Matone, L., Mavalvala, N., McCarthy, R., McClelland, D. E., McHugh, M., McNabb, J. W. C., Melissinos, A., Mendell, G., Mercer, R. A., Meshkov, S., Messaritaki, E., Messenger, C., Mikhailov, E., Mitra, S., Mitrofanov, V. P., Mitselmakher, G., Mittleman, R., Miyakawa, O., Mohanty, S., Moreno, G., Mossavi, K., Mueller, G., Mukherjee, S., Myers, E., Myers, J., Nash, T., Nocera, F., Noel, J. S., O'Reilly, B., O'Shaughnessy, R., Ottaway, D. J., Overmier, H., Owen, B. J., Pan, Y., Papa, M. A., Parameshwaraiah, V., Parameswariah, C., Pedraza, M., Penn, S., Pitkin, M., Prix, R., Quetschke, V., Raab, F., Radkins, H., Rahkola, R., Rakhmanov, M., Rawlins, K., Ray-Majumder, S., Re, V., Regimbau, T., Reitze, D. H., Riesen, R., Riles, K., Rivera, B., Robertson, D. I., Robertson, N. A., Robinson, C., Roddy, S., Rodriguez, A., Rollins, J., Romano, J. D., Romie, J., Rowan, S., Rdiger, A., Ruet, L., Russell, P., Ryan, K., Sandberg, V., Sanders, G. H., Sannibale, V., Sarin, P., Sathyaprakash, B. S., Saulson, P. R., Savage, R., Sazonov, A., Schilling, R., Schofield, R., Schutz, B. F., Schwinberg, P., Scott, S. M., Seader, S. E., Searle, A. C., Sears, B., Sellers, D., Sengupta, A. S., Shawhan, P., Shoemaker, D. H., Sibley, A., Siemens, X., Sigg, D., Sintes, A. M., Smith, J., Smith, M. R., Spjeld, O., Strain, K. A., Strom, D. M., Stuver, A., Summerscales, T., Sung, M., and Sutton, P. J. (2006). Search for gravitational-wave bursts in LIGO's third science run, *Classical and Quantum Gravity* **23**, 8, pp. S29–S39, doi:10.1088/0264-9381/23/8/s05, `http://dx.doi.org/10.1088/0264-9381/23/8/S05`.

Abbott, B., Abbott, R., Adhikari, R., Ajith, P., Allen, B., Allen, G., Amin, R., Anderson, S. B., Anderson, W. G., Arain, M. A., Araya, M., Armandula, H., Armor, P., Aso, Y., Aston, S., Aufmuth, P., Aulbert, C., Babak, S., Ballmer, S., Bantilan, H., Barish, B. C., Barker, C., Barker, D., Barr, B., Barriga, P., Barton, M. A., Bartos, I., Bastarrika, M., Bayer, K., Betzwieser, J., Beyersdorf, P. T., Bilenko, I. A., Billingsley, G., Biswas, R., Black, E., Blackburn, K., Blackburn, L., Blair, D., Bland, B., Bodiya, T. P., Bogue, L., Bork, R., Boschi, V., Bose, S., Brady, P. R., Braginsky, V. B., Brau, J. E., Brinkmann, M., Brooks, A., Brown, D. A., Brunet, G., Bullington, A., Buonanno, A., Burmeister, O., Byer, R. L., Cadonati, L., Cagnoli, G., Camp, J. B., Cannizzo, J., Cannon, K., Cao, J., Cardenas, L., Casebolt, T., Castaldi, G., Cepeda, C., Chalkley, E., Charlton, P., Chatterji, S., Chelkowski, S., Chen, Y., Christensen, N., Clark, D., Clark, J., Cokelaer, T., Conte, R., Cook, D., Corbitt, T., Coyne, D., Creighton, J. D. E., Cumming, A., Cunningham, L., Cutler, R. M., Dalrymple, J., Danzmann, K., Davies, G., DeBra, D., Degallaix, J., Degree, M., Dergachev, V., Desai, S., DeSalvo, R., Dhurandhar, S., Díaz, M., Dickson, J., Credico, A. D., Dietz, A., Donovan, F., Dooley, K. L., Doomes, E. E., Drever, R. W. P., Duke, I., Dumas, J.-C., Dupuis, R. J., Dwyer, J. G., Echols, C., Effler, A., Ehrens, P., Espinoza, E., Etzel, T., Evans, T., Fairhurst, S., Fan, Y., Fazi, D., Fehrmann, H., Fejer, M. M., Finn, L. S., Flasch, K., Fotopoulos, N., Freise, A., Frey, R., Fricke, T., Fritschel, P., Frolov, V. V., Fyffe, M., Garofoli, J., Gholami, I., Giaime, J. A., Giampanis, S., Giardina, K. D., Goda, K., Goetz, E., Goggin, L., González, G., Gossler, S., Gouaty, R., Grant, A., Gras, S., Gray, C., Gray, M., Greenhalgh, R. J. S., Gretarsson, A. M., Grimaldi, F., Grosso, R., Grote, H., Grunewald, S., Guenther, M., Gustafson, E. K., Gustafson, R., Hage, B., Hallam, J. M., Hammer, D., Hanna, C., Hanson, J., Harms, J., Harry, G., Harstad, E., Hayama, K., Hayler, T., Heefner, J., Heng, I. S., Hennessy, M., Heptonstall, A., Hewitson, M., Hild, S., Hirose, E., Hoak, D., Hosken, D., Hough, J., Hughey, B., Huttner, S. H., Ingram, D., Ito, M., Ivanov, A., Johnson, B., Johnson, W. W., Jones, D. I., Jones, G., Jones, R., Ju, L., Kalmus, P., Kalogera, V., Kamat, S., Kanner, J., Kasprzyk, D., Katsavounidis, E., Kawabe, K., Kawamura, S., Kawazoe, F., Kells, W., Keppel, D. G., Khalili, F. Y., Khan, R., Khazanov, E., Kim, C., King, P., Kissel, J. S., Klimenko, S., Kokeyama, K., Kondrashov, V., Kopparapu, R. K., Kozak, D., Kozhevatov, I., Krishnan, B., Kwee, P., Lam, P. K., Landry, M., Lang, M. M., Lantz, B., Lazzarini, A., Lei, M., Leindecker, N., Leonhardt, V., Leonor, I., Libbrecht, K., Lin, H., Lindquist, P., Lockerbie, N. A., Lodhia, D., Lormand, M., Lu, P., Lubinski, M., Lucianetti, A., Lck, H., Machenschalk, B., MacInnis, M., Mageswaran, M., Mailand, K., Mandic, V., Márka, S., Márka, Z., Markosyan, A., Markowitz, J., Maros, E., Martin, I., Martin, R. M., Marx, J. N., Mason, K., Matichard, F., Matone, L., Matzner, R., Mavalvala, N., McCarthy, R., McClelland, D. E., McGuire, S. C., McHugh, M., McIntyre, G., McIvor, G., McKechan, D., McKenzie, K., Meier, T., Melissinos, A., Mendell, G., Mercer, R. A., Meshkov, S., Messenger, C. J., Meyers, D., Miller, J., Minelli, J., Mitra, S., Mitrofanov, V. P., Mitselmakher, G., Mittleman, R., Miyakawa, O., Moe, B., Mohanty, S., Moreno, G., Mossavi, K., MowLowry, C., Mueller, G., Mukherjee, S., Mukhopadhyay, H., Mller-Ebhardt, H., Munch, J., Murray, P., Myers, E., Myers, J., Nash, T., Nelson, J., Newton, G., Nishizawa, A., Numata, K., O'Dell, J., Ogin, G., O'Reilly, B., O'Shaughnessy, R., Ottaway, D. J., Ottens, R. S., Overmier, H., Owen, B. J., Pan, Y., Pankow, C., Papa, M. A., Parameshwaraiah, V., Patel, P., Pedraza, M., Penn, S., Perreca, A., Petrie, T., Pinto, I. M., Pitkin, M., Pletsch, H. J., Plissi, M. V., Postiglione, F., Principe, M., Prix, R., Quetschke, V., Raab, F., Rabeling, D. S., Radkins, H., Rainer, N., Rakhmanov, M., Ramsunder, M., Rehbein, H., Reid, S., Reitze, D. H., Riesen, R., Riles, K., Rivera, B., Robertson, N. A., Robinson, C., Robinson, E. L., Roddy, S., Rodriguez, A., Rogan, A. M., Rollins, J., Romano, J. D., Romie, J., Route, R., Rowan, S., Rdiger, A., Ruet, L., Russell, P., Ryan, K., Sakata, S., Samidi, M., de la Jordana, L. S., Sandberg, V., Sannibale, V., Saraf, S., Sarin, P., Sathyaprakash, B. S., Sato, S., Saulson, P. R., Savage, R., Savov, P., Schediwy, S. W., Schilling, R., Schnabel, R., Schofield, R., Schutz, B. F., Schwinberg, P., Scott, S. M., Searle, A. C., Sears, B., Seifert, F., Sellers, D., Sengupta, A. S., Shawhan, P., Shoemaker, D. H., Sibley, A., Siemens, X., Sigg, D., Sinha, S., Sintes, A. M., Slagmolen, B. J. J., Slutsky, J., Smith, J. R., Smith, M. R., Smith, N. D., Somiya, K., (2008). First joint search for gravitational-wave bursts in LIGO and GEO 600 data, *Classical and Quantum Gravity* **25**, 24, p. 245008, doi:10.1088/0264-9381/25/24/245008, http://dx.doi.org/10.1088/0264-9381/25/24/245008.

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., and et al. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger, *Physical Review Letters* **116**, 6, 061102, doi:10.1103/PhysRevLett.116.061102, arXiv:1602.03837 [gr-qc].

Abbott, B. P., Abbott, R., Adhikari, R., Ajith, P., Allen, B., Allen, G., Amin, R. S., Anderson, S. B., Anderson, W. G., Arain, M. A., Araya, M., Armandula, H., Armor, P., Aso, Y., Aston, S., Aufmuth, P., Aulbert, C., Babak, S., Baker, P., Ballmer, S., Barker, C., Barker, D., Barr, B., Barriga, P., Barsotti, L., Barton, M. A., Bartos, I., Bassiri, R., Bastarrika, M., Behnke, B., Benacquista, M., Betzwieser, J., Beyersdorf, P. T., Bilenko, I. A., Billingsley, G., Biswas, R., Black, E., Blackburn, J. K., Blackburn, L., Blair, D., Bland, B., Bodiya, T. P., Bogue, L., Bork, R., Boschi, V., Bose, S., Brady, P. R., Braginsky, V. B., Brau, J. E., Bridges, D. O., Brinkmann, M., Brooks, A. F., Brown, D. A., Brummit, A., Brunet, G., Bullington, A., Buonanno, A., Burmeister, O., Byer, R. L., Cadonati, L., Camp, J. B., Cannizzo, J., Cannon, K. C., Cao, J., Cardenas, L., Caride, S., Castaldi, G., Caudill, S., Cavaglià, M., Cepeda, C., Chalermsongsak, T., Chalkley, E., Charlton, P., Chatterji, S., Chelkowski, S., Chen, Y., Christensen, N., Chung, C. T. Y., Clark, D., Clark, J., Clayton, J. H., Cokelaer, T., Colacino, C. N., Conte, R., Cook, D., Corbitt, T. R. C., Cornish, N., Coward, D., Coyne, D. C., Creighton, J. D. E., Creighton, T. D., Cruise, A. M., Culter, R. M., Cumming, A., Cunningham, L., Danilishin, S. L., Danzmann, K., Daudert, B., Davies, G., Daw, E. J., DeBra, D., Degallaix, J., Dergachev, V., Desai, S., DeSalvo, R., Dhurandhar, S., Díaz, M., Dietz, A., Donovan, F., Dooley, K. L., Doomes, E. E., Drever, R. W. P., Dueck, J., Duke, I., Dumas, J.-C., Dwyer, J. G., Echols, C., Edgar, M., Effler, A., Ehrens, P., Espinoza, E., Etzel, T., Evans, M., Evans, T., Fairhurst, S., Faltas, Y., Fan, Y., Fazi, D., Fehrmenn, H., Finn, L. S., Flasch, K., Foley, S., Forrest, C., Fotopoulos, N., Franzen, A., Frede, M., Frei, M., Frei, Z., Freise, A., Frey, R., Fricke, T., Fritschel, P., Frolov, V. V., Fyffe, M., Galdi, V., Garofoli, J. A., Gholami, I., Giaime, J. A., Giampanis, S., Giardina, K. D., Goda, K., Goetz, E., Goggin, L. M., González, G., Gorodetsky, M. L., Goßler, S., Gouaty, R., Grant, A., Gras, S., Gray, C., Gray, M., Greenhalgh, R. J. S., Gretarsson, A. M., Grimaldi, F., Grosso, R., Grote, H., Grunewald, S., Guenther, M., Gustafson, E. K., Gustafson, R., Hage, B., Hallam, J. M., Hammer, D., Hammond, G. D., Hanna, C., Hanson, J., Harms, J., Harry, G. M., Harry, I. W., Harstad, E. D., Haughian, K., Hayama, K., Heefner, J., Heng, I. S., Heptonstall, A., Hewitson, M., Hild, S., Hirose, E., Hoak, D., Hodge, K. A., Holt, K., Hosken, D. J., Hough, J., Hoyland, D., Hughey, B., Huttner, S. H., Ingram, D. R., Isogai, T., Ito, M., Ivanov, A., Johnson, B., Johnson, W. W., Jones, D. I., Jones, G., Jones, R., Ju, L., Kalmus, P., Kalogera, V., Kandhasamy, S., Kanner, J., Kasprzyk, D., Katsavounidis, E., Kawabe, K., Kawamura, S., Kawazoe, F., Kells, W., Keppel, D. G., Khalaidovski, A., Khalili, F. Y., Khan, R., Khazanov, E., King, P., Kissel, J. S., Klimenko, S., Kokeyama, K., Kondrashov, V., Kopparapu, R., Koranda, S., Kozak, D., Krishnan, B., Kumar, R., Kwee, P., Lam, P. K., Landry, M., Lantz, B., Lazzarini, A., Lei, H., Lei, M., Leindecker, N., Leonor, I., Li, C., Lin, H., Lindquist, P. E., Littenberg, T. B., Lockerbie, N. A., Lodhia, D., Longo, M., Lormand, M., Lu, P., Lubinski, M., Lucianetti, A., Lck, H., Machenschalk, B., MacInnis, M., Mageswaran, M., Mailand, K., Mandel, I., Mandic, V., Márka, S., Márka, Z., Markosyan, A., Markowitz, J., Maros, E., Martin, I. W., Martin, R. M., Marx, J. N., Mason, K., Matichard, F., Matone, L., Matzner, R. A., Mavalvala, N., McCarthy, R., McClelland, D. E., McGuire, S. C., McHugh, M., McIntyre, G., McKechan, D. J. A., McKenzie, K., Mehmet, M., Melatos, A., Melissinos, A. C., Menéndez, D. F., Mendell, G., Mercer, R. A., Meshkov, S., Messenger, C., Meyer, M. S., Miller, J., Minelli, J., Mino, Y., Mitrofanov, V. P., Mitselmakher, G., Mittleman, R., Miyakawa, O., Moe, B., Mohanty, S. D., Mohapatra, S. R. P., Moreno, G., Morioka, T., Mors, K., Mossavi, K., MowLowry, C., Mueller, G., Mller-Ebhardt, H., Muhammad, D., Mukherjee, S., Mukhopadhyay, H., Mullavey, A., Munch, J., Murray, P. G., Myers, E., Myers, J., Nash, T., Nelson, J., Newton, G., Nishizawa, A., Numata, K., O'Dell, J., O'Reilly, B., O'Shaughnessy, R., Ochsner, E., Ogin, G. H., Ottaway, D. J., Ottens, R. S., Overmier, H., Owen, B. J., Pan, Y., Pankow, C., Papa, M. A., Parameshwaraiah, V., Patel, P., Pedraza, M., Penn, S., Perraca, A., Pierro, V., Pinto, I. M., Pitkin, M., Pletsch, H. J., Plissi, M. V., Postiglione, F., Principe, M., Prix, R., Prokhorov, L., Punken, O., Quetschke, V., Raab, F. J., Rabeling, D. S., Radkins, H., Raffai, P., Raics, Z., Rainer, N., Rakhmanov, M., Raymond, V., Reed, C. M., Reed, T., Rehbein, H., Reid, S., Reitze, D. H., Riesen, R., Riles, K., Rivera, B., Roberts, P., Robertson, N. A., Robinson, C., Robinson, E. L (2009). LIGO: the laser interferometer gravitational-wave observatory, *Reports on Progress in Physics* **72**, 7, p. 076901, doi:10.1088/0034-4885/72/7/076901, `http://dx.doi.org/10.1088/0034-4885/72/7/076901`.

Abramovici, A., Althouse, W. E., Drever, R. W. P., Gursel, Y., Kawamura, S., Raab, F. J., Shoemaker, D., Sievers, L., Spero, R. E., Thorne, K. S., Vogt, R. E., Weiss, R., Whitcomb, S. E., and Zucker, M. E. (1992). LIGO: The laser interferometer gravitational-wave observatory, *Science* **256**, 5055, pp. 325–333, doi:10.1126/science.256.5055.325, `http://dx.doi.org/10.1126/science.256.5055.325`.

Accadia, T., Acernese, F., Alshourbagy, M., Amico, P., Antonucci, F., Aoudia, S., Arnaud, N., Arnault, C., Arun, K. G., Astone, P., Avino, S., Babusci, D., Ballardin, G., Barone, F., Barrand, G., Barsotti, L., Barsuglia, M., Basti, A., Bauer, T. S., Beauville, F., Bebronne, M., Bejger, M., Beker, M. G., Bellachia, F., Belletoile, A., Beney, J. L., Bernardini, M., Bigotta, S., Bilhaut, R., Birindelli, S., Bitossi, M., Bizouard, M. A., Blom, M., Boccara, C., Boget, D., Bondu, F., Bonelli, L., Bonnand, R., Boschi, V., Bosi, L., Bouedo, T., Bouhou, B., Bozzi, A., Bracci, L., Braccini, S., Bradaschia, C., Branchesi, M., Briant, T., Brillet, A., Brisson, V., Brocco, L., Bulik, T., Bulten, H. J., Buskulic, D., Buy, C., Cagnoli, G., Calamai, G., Calloni, E., Campagna, E., Canuel, B., Carbognani, F., Carbone, L., Cavalier, F., Cavalieri, R., Cecchi, R., Cella, G., Cesarini, E., Chassande-Mottin, E., Chatterji, S., Chiche, R., Chincarini, A., Chiummo, A., Christensen, N., Clapson, A. C., Cleva, F., Coccia, E., Cohadon, P. F., Colacino, C. N., Colas, J., Colla, A., Colombini, M., Conforto, G., Corsi, A., Cortese, S., Cottone, F., Coulon, J. P., Cuoco, E., D'Antonio, S., Daguin, G., Dari, A., Dattilo, V., David, P. Y., Davier, M., Day, R., Debreczeni, G., Carolis, G. D., Dehamme, M., Fabbro, R. D., Pozzo, W. D., del Prete, M., Derome, L., Rosa, R. D., DeSalvo, R., Dialinas, M., Fiore, L. D., Lieto, A. D., Emilio, M. D. P., Virgilio, A. D., Dietz, A., Doets, M., Dominici, P., Dominjon, A., Drago, M., Drezen, C., Dujardin, B., Dulach, B., Eder, C., Eleuteri, A., Enard, D., Evans, M., Fabbroni, L., Fafone, V., Fang, H., Ferrante, I., Fidecaro, F., Fiori, I., Flaminio, R., Forest, D., Forte, L. A., Fournier, J. D., Fournier, L., Franc, J., Francois, O., Frasca, S., Frasconi, F., Freise, A., Gaddi, A., Galimberti, M., Gammaitoni, L., Ganau, P., Garnier, C., Garufi, F., Gáspár, M. E., Gemme, G., Genin, E., Gennai, A., Gennaro, G., Giacobone, L., Giazotto, A., Giordano, G., Giordano, L., Girard, C., Gouaty, R., Grado, A., Granata, M., Granata, V., Grave, X., Greverie, C., Groenstege, H., Guidi, G. M., Hamdani, S., Hayau, J. F., Hebri, S., Heidmann, A., Heitmann, H., Hello, P., Hemming, G., Hennes, E., Hermel, R., Heusse, P., Holloway, L., Huet, D., Iannarelli, M., Jaranowski, P., Jehanno, D., Journet, L., Karkar, S., Ketel, T., Voet, H., Kovalik, J., Kowalska, I., Kreckelbergh, S., Krolak, A., Lacotte, J. C., Lagrange, B., Penna, P. L., Laval, M., Marec, J. C. L., Leroy, N., Letendre, N., Li, T. G. F., Lieunard, B., Liguori, N., Lodygensky, O., Lopez, B., Lorenzini, M., Loriette, V., Losurdo, G., Loupias, M., Mackowski, J. M., Maiani, T., Majorana, E., Magazzù, C., Maksimovic, I., Malvezzi, V., Man, N., Mancini, S., Mansoux, B., Mantovani, M., Marchesoni, F., Marion, F., Marin, P., Marque, J., Martelli, F., Masserot, A., Massonnet, L., Matone, G., Matone, L., Mazzoni, M., Menzinger, F., Michel, C., Milano, L., Minenkov, Y., Mitra, S., Mohan, M., Montorio, J. L., Morand, R., Moreau, F., Moreau, J., Morgado, N., Morgia, A., Mosca, S., Moscatelli, V., Mours, B., Mugnier, P., Mul, F. A., Naticchioni, L., Neri, I., Nocera, F., Pacaud, E., Pagliaroli, G., Pai, A., Palladino, L., Palomba, C., Paoletti, F., Paoletti, R., Paoli, A., Pardi, S., Parguez, G., Parisi, M., Pasqualetti, A., Passaquieti, R., Passuello, D., Perciballi, M., Perniola, B., Persichetti, G., Petit, S., Pichot, M., Piergiovanni, F., Pietka, M., Pignard, R., Pinard, L., Poggiani, R., Popolizio, P., Pradier, T., Prato, M., Prodi, G. A., Punturo, M., Puppo, P., Qipiani, K., Rabaste, O., Rabeling, D. S., Rácz, I., Raffaelli, F., Rapagnani, P., Rapisarda, S., Re, V., Reboux, A., Regimbau, T., Reita, V., Remilleux, A., Ricci, F., Ricciardi, I., Richard, F., Ripepe, M., Robinet, F., Rocchi, A., Rolland, L., Romano, R., Rosińska, D., Roudier, P., Ruggi, P., Russo, G., Salconi, L., Sannibale, V., Sassolas, B., Sentenac, D., Solimeno, S., Sottile, R., Sperandio, L., Stanga, R., Sturani, R., Swinkels, B., Tacca, M., Taddei, R., Taffarello, L., Tarallo, M., Tissot, S., Toncelli, A., Tonelli, M., Torre, O., Tournefier, E., Travasso, F., Tremola, C., Turri, E., Vajente, G., van den Brand, J. F. J., Broeck, C. V. D., van der Putten, S., Vasuth, M., Vavoulidis, M., Vedovato, G., Verkindt, D., Vetrano, F., Véziant, O., Viceré, A., Vinet, J. Y., Vilalte, S., Vitale, S., Vocca, H., Ward, R. L., Was, M., Yamamoto, K., Yvert, M., Zendri, J. P., and Zhang, Z. (2012). Virgo: a laser interferometer to detect gravitational waves, *Journal of Instrumentation* **7**, 03, pp. P03012–P03012, doi:10.1088/1748-0221/7/03/p03012, `http://dx.doi.org/10.1088/1748-0221/7/03/P03012`.

Anderson, D. Z. (1984). Alignment of resonant optical cavities, *Applied Optics* **23**, pp. 2944–2949, doi:10.1364/AO.23.002944.

Ando, M. and the TAMA collaboration (2002). Current status of TAMA, *Class. Quantum Grav.* **19**, 7, pp. 1409–1419, doi:10.1088/0264-9381/19/7/324, `http://dx.doi.org/10.1088/0264-9381/19/7/324`.

Arain, M. A. and Mueller, G. (2008). Design of the Advanced LIGO recycling cavities, *Optics Express* **16**, p. 10018, doi:10.1364/oe.16.010018.

Aston, S. M., Barton, M. A., Bell, A. S., Beveridge, N., Bland, B., Brummitt, A. J., Cagnoli, G., Cantley, C. A., Carbone, L., Cumming, A. V., Cunningham, L., Cutler, R. M., Greenhalgh, R. J. S., Hammond, G. D., Haughian, K., Hayler, T. M., Heptonstall, A., Heefner, J., Hoyland, D., Hough, J., Jones, R., Kissel, J. S., Kumar, R., Lockerbie, N. A., Lodhia, D., Martin, I. W., Murray, P. G., O'Dell, J., Plissi, M. V., Reid, S., Romie, J., Robertson, N. A., Rowan, S., Shapiro, B., Speake, C. C., Strain, K. A., Tokmakov, K. V., Torrie, C., van Veggel, A. A., Vecchio, A., and Wilmut, I. (2012). Update on quadruple suspension design for advanced LIGO, *Class. Quantum Grav.* **29**, 23, p. 235004, doi:10.1088/0264-9381/29/23/235004, `http://dx.doi.org/10.1088/0264-9381/29/23/235004`.

Dewey, D., Linsay, P. S., Livas, J., Weiss, R., and Shoemaker, D. H. (1984). The MIT Prototype Gravitational Wave Detector: A Status Report, in *Bulletin of the American Astronomical Society*, *Bulletin of the American Astronomical Society*, Vol. 16, p. 517.

Drever, R. W. P., Hall, J. L., Kowalski, F. V., Hough, J., Ford, G. M., Munley, A. J., and Ward, H. (1983). Laser phase and frequency stabilization using an optical resonator, *Applied Physics B: Lasers and Optics* **31**, pp. 97–105, doi:10.1007/BF00702605.

Dwyer, S., Sigg, D., Ballmer, S. W., Barsotti, L., Mavalvala, N., and Evans, M. (2015). Gravitational wave detector with cosmological reach, *Physical Review D: Particles and Fields* **91**, 8, 082001, doi:10.1103/PhysRevD.91.082001, `arXiv:1410.0612 [astro-ph.IM]`.

Forward, R. L. (1978). Wideband laser-interferometer graviational-radiation experiment, *Physical Review D* **17**, 2, pp. 379–390, doi:10.1103/physrevd.17.379, `http://dx.doi.org/10.1103/PhysRevD.17.379`.

Fritschel, P., Mavalvala, N., Shoemaker, D., Sigg, D., Zucker, M., and González, G. (1998). Alignment of an Interferometric Gravitational Wave Detector, *Applied Optics* **37**, pp. 6734–6747, doi:10.1364/AO.37.006734.

Giaime, J., Saha, P., Shoemaker, D., and Sievers, L. (1996). A passive vibration isolation stack for LIGO: Design, modeling, and testing, *Review of Scientific Instruments* **67**, 1, p. 208, doi:10.1063/1.1146573, `http://dx.doi.org/10.`

1063/1.1146573.

Grote, H. (2010). The GEO 600 status, *Class. Quantum Grav.* **27**, 8, p. 084003, doi:10.1088/0264-9381/27/8/084003, http://dx.doi.org/10.1088/0264-9381/27/8/084003.

Grote, H., Danzmann, K., Dooley, K. L., Schnabel, R., Slutsky, J., and Vahlbruch, H. (2013). First long-term application of squeezed states of light in a gravitational-wave observatory, *Phys. Rev. Lett.* **110**, 18, doi:10.1103/physrevlett.110.181101, http://dx.doi.org/10.1103/PhysRevLett.110.181101.

Hild, S., Grote, H., Degallaix, J., Chelkowski, S., Danzmann, K., Freise, A., Hewitson, M., Hough, J., Lück, H., Prijatelj, M., Strain, K. A., Smith, J. R., and Willke, B. (2009). DC-readout of a signal-recycled gravitational wave detector, *Classical and Quantum Gravity* **26**, 5, 055012, doi:10.1088/0264-9381/26/5/055012, arXiv:0811.3242 [gr-qc].

Klimenko, S., Vedovato, G., Drago, M., Salemi, F., Tiwari, V., Prodi, G. A., Lazzaro, C., Ackley, K., Tiwari, S., Silva, C. F. D., and Mitselmakher, G. (2016). Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors, *Physical Review D* **93**, 4, doi:10.1103/physrevd.93.042004, http://dx.doi.org/10.1103/PhysRevD.93.042004.

Kwee, P., Bogan, C., Danzmann, K., Frede, M., Kim, H., King, P., Pld, J., Puncken, O., Savage, R. L., Seifert, F., Wessels, P., Winkelmann, L., and Willke, B. (2012). Stabilized high-power laser system for the gravitational wave detector advanced LIGO, *Opt. Express* **20**, 10, p. 10617, doi:10.1364/oe.20.010617, http://dx.doi.org/10.1364/OE.20.010617.

Lorenzini, M. (2010). The monolithic suspension for the virgo interferometer, *Class. Quantum Grav.* **27**, 8, p. 084021, doi:10.1088/0264-9381/27/8/084021, http://dx.doi.org/10.1088/0264-9381/27/8/084021.

Matichard, F. *et al.* (2015). Seismic isolation of Advanced LIGO: Review of strategy, instrumentation and performance, *Class. Quant. Grav.* **32**, 18, p. 185003, doi:10.1088/0264-9381/32/18/185003, arXiv:1502.06300 [physics.ins-det].

Morrison, E., Robertson, D. I., Ward, H., and Meers, B. J. (1994a). Automatic alignment of optical interferometers, *Applied Optics* **33**, pp. 5041–5049, doi:10.1364/AO.33.005041.

Morrison, E., Robertson, D. I., Ward, H., and Meers, B. J. (1994b). Experimental demonstration of an automatic alignment system for optical interferometers, *Applied Optics* **33**, pp. 5037–5040.

Mueller, C. L., Arain, M. A., Ciani, G., DeRosa, R. T., Effler, A., Feldbaum, D., Frolov, V. V., Fulda, P., Gleason, J., Heintze, M., Kawabe, K., King, E. J., Kokeyama, K., Korth, W. Z., Martin, R. M., Mullavey, A., Peold, J., Quetschke, V., Reitze, D. H., Tanner, D. B., Vorvick, C., Williams, L. F., and Mueller, G. (2016). The advanced LIGO input optics, *Rev. Sci. Instrum.* **87**, 1, p. 014502, doi:10.1063/1.4936974, http://dx.doi.org/10.1063/1.4936974.

Plissi, M. V., Torrie, C. I., Husman, M. E., Robertson, N. A., Strain, K. A., Ward, H., Luck, H., and Hough, J. (2000). GEO 600 triple pendulum suspension system: Seismic isolation and control, *Rev. Sci. Instrum.* **71**, 6, p. 2539, doi:10.1063/1.1150645, `http://dx.doi.org/10.1063/1.1150645`.

Punturo, M. and et al. (2010). The Einstein Telescope: a third-generation gravitational wave observatory, *Classical and Quantum Gravity* **27**, 19, 194002, doi:10.1088/0264-9381/27/19/194002.

Robertson, D. I., Morrison, E., Hough, J., Killbourn, S., Meers, B. J., Newton, G. P., Robertson, N. A., Strain, K. A., and Ward, H. (1995). The glasgow 10 m prototype laser interferometric gravitational wave detector, *Rev. Sci. Instrum.* **66**, 9, p. 4447, doi:10.1063/1.1145339, `http://dx.doi.org/10.1063/1.1145339`.

Shoemaker, D., Schilling, R., Schnupp, L., Winkler, W., Maischberger, K., and Rüdiger, A. (1988). Noise behavior of the Garching 30-meter prototype gravitational-wave detector, *Physical Review D: Particles and Fields* **38**, pp. 423–432, doi:10.1103/PhysRevD.38.423.

Spero, R. (1989). Status Report on the Caltech 40-METER Fabry-Perot Prototype Gravitational Wave Detector, in *General Relativity and Gravitation*, p. 584.

Staley, A., Martynov, D., Abbott, R., Adhikari, R. X., Arai, K., Ballmer, S., Barsotti, L., Brooks, A. F., DeRosa, R. T., Dwyer, S., Effler, A., Evans, M., Fritschel, P., Frolov, V. V., Gray, C., Guido, C. J., Gustafson, R., Heintze, M., Hoak, D., Izumi, K., Kawabe, K., King, E. J., Kissel, J. S., Kokeyama, K., Landry, M., McClelland, D. E., Miller, J., Mullavey, A., O'Reilly, B., Rollins, J. G., Sanders, J. R., Schofield, R. M. S., Sigg, D., Slagmolen, B. J. J., Smith-Lefebvre, N. D., Vajente, G., Ward, R. L., and Wipf, C. (2014). Achieving resonance in the Advanced LIGO gravitational-wave interferometer, *Classical and Quantum Gravity* **31**, 24, 245010, doi:10.1088/0264-9381/31/24/245010.

Uchiyama, T., Miyoki, S., Telada, S., Yamamoto, K., Ohashi, M., Agatsuma, K., Arai, K., Fujimoto, M.-K., Haruyama, T., Kawamura, S., Miyakawa, O., Ohishi, N., Saito, T., Shintomi, T., Suzuki, T., Takahashi, R., and Tatsumi, D. (2012). Reduction of thermal fluctuations in a cryogenic laser interferometric gravitational wave detector, *Phys. Rev. Lett.* **108**, 14, doi:10.1103/physrevlett.108.141101, `http://dx.doi.org/10.1103/PhysRevLett.108.141101`.

Weiss, R. (1972). Electromagnetically coupled gravitational antenna, , Quarterly progress report, Research Laboratory of Electronics, MIT.

Willke, B., Aufmuth, P., Aulbert, C., Babak, S., Balasubramanian, R., Barr, B. W., Berukoff, S., Bose, S., Cagnoli, G., Casey, M. M., Churches, D., Clubley, D., Colacino, C. N., Crooks, D. R. M., Cutler, C., Danzmann, K., Davies, R., Dupuis, R., Elliffe, E., Fallnich, C., Freise, A., Goßler, S., Grant, A., Grote, H., Heinzel, G., Heptonstall, A., Heurs, M., Hewitson, M., Hough, J., Jennrich, O., Kawabe, K., Ktter, K., Leonhardt, V., Lck, H., Malec, M., McNamara, P. W., McIntosh, S. A., Mossavi, K., Mohanty, S., Mukherjee, S., Nagano, S., Newton, G. P., Owen, B. J., Palmer, D., Papa, M. A., Plissi, M. V., Quetschke, V., Robertson, D. I., Robertson,

N. A., Rowan, S., Rdiger, A., Sathyaprakash, B. S., Schilling, R., Schutz, B. F., Senior, R., Sintes, A. M., Skeldon, K. D., Sneddon, P., Stief, F., Strain, K. A., Taylor, I., Torrie, C. I., Vecchio, A., Ward, H., Weiland, U., Welling, H., Williams, P., Winkler, W., Woan, G., and Zawischa, I. (2002). The GEO 600 gravitational wave detector, *Class. Quantum Grav.* **19**, 7, pp. 1377–1387, doi:10.1088/0264-9381/19/7/321, `http://dx.doi.org/10.1088/0264-9381/19/7/321`.