The status of laser interferometer gravitational-wave detectors

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Abstract. There has been a rapid advance in the sensitivity of broadband searches for gravitational waves, using an international network of kilometer-scale laser interferometers. The LIGO detectors in North America, the GEO600 detector in Germany and the TAMA300 detector in Japan have conducted searches for gravitational waves covering a frequency range from below 100 Hz up to many kHz. These detectors and the VIRGO detector in Italy are in a mature state of commissioning and technology development for a generation of more advanced detectors is ongoing.

1. Introduction
Laser interferometer gravitational-wave detectors use freely suspended mirrors to mark the position of inertial frames in space [1]. The spatial strain produced by a gravitational wave will cause motion of these frames that can be detected using laser light. This is illustrated schematically in figure 1.

Figure 1. Schematic of gravitational wave strain and laser interferometer detector.
Centered in the upper part of the figure, is a circle of points in space. To its left is shown the expected distortions of the circle of points when a gravitational wave, propagating vertically into the page with a particular polarization, reaches a maximum positive strain. To the right is the image when the gravitational wave reaches its maximum negative strain. The strain stretches one axis of space...
transverse to the propagating gravitational wave while simultaneously shrinking the perpendicular axis transverse to the wave. The strain amplitude $h$ is the difference in the major and minor axes of the resulting ellipse, divided by the diameter of the original circle. The bottom part of the figure shows a schematic laser interferometer, with a beam-splitting mirror marking the center of the circle and two mirrors marking the edge of the circle, separated by 90 degrees. As space expands and contracts the free mirrors follow the points in space. Laser light transiting the interferometer picks up a phase shift depending on the RELATIVE lengths of the two arms, which is detected at the photodetector.

The strain-induced phase shift is increased if the light makes multiple passes in each arm before it recombines on the beam splitter. Multiple passes can be achieved by creating Fabry-Perot cavities in each arm by adding two additional mirrors near the beam splitter, as shown in figure 2.

![Figure 2. Schematic of a power-recycled Fabry-Perot-Michelson interferometer.](image)

In this configuration, the phase shifts induced by the gravitational-wave strain are increased by approximately the number of times light traverses the arms. Furthermore, if the mirrors are arranged (in the absence of a gravitational wave) so that the two arms are equal (modulo half a wavelength of the light), then the interference signal at the photodetector depends only on the differences in the interaction of the light in the two arms. Small common-mode changes, such as those due to a change in amplitude or frequency of the light, create signals on the light that travels back toward the laser.

A control system maintains the interferometer in this “balanced” state at all times. Modulating the phase of the light injected into the interferometer and measuring the resulting amplitude modulation of light in different parts of the interferometer allows the recovery of the optical phase [2]. The effect of any gravitational wave is recorded on the control signals that maintain this condition. These control signals are calibrated by applying small, known forces to the mirrors that mimic the response to a gravitational wave. Since the interferometer in maintained in this balanced state by the control system, signals are recovered with relatively little light absorbed at the photodetector, so most of the light is returned toward the laser. A power-recycling mirror re-directs this light back into the interferometer. Typically each photon is recycled approximately 50 times in this type of interferometer.

The sensitivity of gravitational-wave detectors is limited by fundamental and practical concerns as shown in figure 3. The vertical axis gives the noise-equivalent strain that would be obtained in a 1 Hz bandwidth and the horizontal axis gives the frequency of operation.
At high frequencies, the quantum nature of light gives rise to shot noise on recombination of photons at the beam splitter. This noise limits the smallest strain that can be sensed. Background motion of the mirrors (not due to gravitational waves) will limit sensitivity at lower frequencies. At the lowest frequencies there is a vibration background that arises due to seismic and man-made sources. This cannot be eliminated, since we rely on a solid connection to Earth to support our mirrors against Earth’s gravity. Vibration is mitigated by cascaded low-pass mechanical filters, which give rise to a sharp seismic cut-off. In the intermediate range of frequencies, the only remaining vibrations should be the cumulative effects of vibrations of the atoms comprising the suspended mirrors of the interferometer. These vibrations are in thermal equilibrium with the room-temperature environment of these components, so we expect an average energy of $k_B T$ per mode, where $k_B$ is Boltzmann’s constant and $T$ is the temperature. This “thermal noise” can be separated into motions arising from the mirror substrate (test mass) and the suspension fibers. The same photon fluctuations that give rise to shot noise also cause an irreducible background of radiation pressure fluctuations on the mirrors. The interplay of shot noise and radiation pressure enforces the Heisenberg uncertainty principle for these macroscopic detectors. The sensitive region above the sum of these noise sources defines the signal band for gravitational-wave interferometers.

There are also limits imposed by the observatory environment and facilities. The most fundamental limit is the gravitational gradient noise of Earth, which sets the low-frequency bound for terrestrial detectors. Fluctuations in the column density of residual gas in the kilometer-scale beam tubes of these interferometers induce phase shifts on the light that mimic the effect of gravitational wave strains. Stringent requirements on the vacuum in these beam tubes mitigate this noise. Finally, the small clear aperture of these long beam tubes require baffling to prevent stray light from glancing reflections from the beam-tube walls which cannot be vibration isolated. The efficacy of the baffling determines the “stray light” limit in figure 3.

2. The international detector network
Kilometer-scale laser interferometers in North America, Europe and Asia have been operated as part of a worldwide detection network. In North America, the NSF-sponsored LIGO operates detectors (fig 4) at two facilities in the US incorporating interferometers in an L-shaped vacuum system with 4-km arm lengths. A 4-km interferometer (H1) and a 2-km interferometer (H2), using independent components, share this vacuum at the Hanford, Washington facility. A single 4-km interferometer (L1)
occupies a similar vacuum system at the Livingston, Louisiana facility. These facilities were designed
to house a succession of interferometers of increasing sophistication and sensitivity as the critical
technologies for these instruments evolve. The Initial LIGO interferometer [3] was designed to have a
plausible, if not probable, chance to make the first detections of gravitational waves, while a far more
powerful detector, known as Advanced LIGO was under development. Advanced LIGO was intended
to make gravitational-wave detections a common occurrence. Caltech and MIT operate the LIGO
facilities and support labs on their campuses for the LIGO Scientific Collaboration. The collaboration,
which includes 500 scientists and engineers on four continents, sets the scientific agenda for LIGO,
supporting operations, data analysis and technology development for future upgrades.

The VIRGO detector (fig 5) is a 3-km instrument [4] situated in Cascina (near Pisa), Italy, operated
by a collaboration of scientists from Italy and France. VIRGO employs a similar configuration to the
LIGO detectors, but has a more advanced vibration-isolation system. VIRGO sensitivity should
eventually be comparable to the Initial LIGO detector over most of its frequency band, but it can
operate at lower frequencies, comparable to the Advanced LIGO detector.

The GEO600 detector (fig 5) near Hannover, Germany [5] is operated by the GEO collaboration of
scientists from Germany and the United Kingdom. It name derives from the 600-meter length of its
arms. GEO personnel are members of the LIGO Scientific Collaboration as well. Because of its
shorter arms, GEO600 is not expected to achieve a sensitivity comparable to LIGO, but more
advanced suspension and vibration-isolation technologies should close some of that gap. GEO600 also
uses a signal-recycling mirror at the gravitational wave detection port. This mirror causes gravitational
wave signals on the light to resonate in the interferometer within a certain band of frequencies.
Changing the reflectivity and position of this mirror allows the response of the interferometer to be tuned. One can choose to operate in a relatively broad band mode or as a narrowly tuned detector. Many of these features and all of this experience will be incorporated into Advanced LIGO interferometers.

![Figure 6. TAMA300 (left) and Gingin site (right).](image)

TAMA300 (Fig 6) near Tokyo, Japan [6] has 300-meter arm lengths. The basic optical configuration is similar to that employed in the LIGO and VIRGO detectors. Because of its smaller size, TAMA300 cannot achieve the sensitivity of the larger interferometers, but it was the first of these large-scale detectors to come into operation.

The Gingin site in Western Australia currently has a small interferometer being used to test Advanced LIGO optics (fig 6). It is hoped that this site could eventually be expanded to house a 3-km interferometer in the Southern Hemisphere.

3. Gravitational-wave searches

The various laser interferometer groups have adopted a common data format to minimize technical barriers to combined data analysis. The VIRGO detector is still in a commissioning phase and it is expected that the first VIRGO observing runs will begin in approximately a year. The most sensitive searches done to date have been LIGO observing runs, conducted in coincidence with GEO600, TAMA300 and the Allegro and AURIGA resonant-mass detectors. These runs were planned well in advance to coordinate the commissioning and observing schedules of these detectors as much as possible. The four science runs were conducted when dramatically new levels of sensitivity were achieved (fig 7) for LIGO’s detectors. These runs were scheduled to last from a few weeks to a few months to identify if there were frequent events at the new sensitivity level before engaging in more exhaustive commissioning efforts to extend the range of the detectors.

The S1 data run included coincident operation of LIGO’s interferometers with GEO600 for 17 days in August/September 2002, with TAMA300 operating on two of those days. For S2, LIGO ran with TAMA300 from February 14 to April 14, 2003. LIGO ran S3 from October 31, 2003 until January 9, 2004, with GEO600, TAMA300 and Allegro for different durations. After a long commissioning period, LIGO ran S4 from February 22 until March 23, 2005 in coincidence with GEO600, Allegro and AURIGA. Further commissioning work has brought the Initial LIGO interferometers to their design sensitivity with a duty cycle that makes an extended duration run possible. S5 is scheduled to run from November, 2005 through 2007, acquiring an integrated year of coincidence data between the two LIGO facilities and whatever other detectors can join the run during this time. Figure 7 gives an indication of the evolution of LIGO detector sensitivity for these science runs.
A benchmark figure of merit has been adopted by LIGO to reflect the broad-band sensitivity of a detector. The inspiral to coalescence of a pair of neutron stars is expected to produce a chirp waveform that sweeps from the low-frequency seismic cutoff up to frequencies in the range of 1 kHz. We estimate the distance at which the inspiral of a pair of 1.4-solar-mass neutron stars could be seen with high confidence for sources in various sky positions. The average over sky positions gives the “Inspiral Range” quoted in figure 7. An improvement of approximately three orders of magnitude has been achieved over a progression of science runs in the past three years, extending the searchable volume of space by nearly a factor of a billion.

The original target for the Initial LIGO detector was to achieve a noise-equivalent strain of $10^{-21}$ RMS in a 100-Hz bandwidth at the frequency of peak sensitivity. Although this was achieved in the S3 run, the duty cycle of the detectors was impaired by man-made sources of noise, particularly logging near the Louisiana facility. An active seismic attenuation system, consisting of sensors and hydraulic actuators mounted external to the vacuum chambers, was installed at the Louisiana observatory during the long break between S3 and S4. This resulted in a threefold increase in observing duty cycle at Louisiana during the month-long S4 run, despite a several day interruption due to failure of the electrical power connection to the site. The most recent spectrum also shows a significant improvement in sensitivity at frequencies above 100 Hz, as we increased the laser power injected into the interferometers to reduce the influence of shot noise. To handle larger laser powers it is important to match the wavefront of the light to the figures of the mirrors, overcoming both manufacturing tolerances and differences in heating of the mirrors by small amounts of absorbed laser power. A thermal compensation system has been installed to allow adaptive tuning of the optical profiles of the mirrors by selectively applying heat from a CO$_2$ laser to certain zones of the mirrors.

4. Data analysis
The data have been searched by a variety of methods for gravitational waves. There are four qualitative categories of searches: for periodic sources, such as spinning neutron stars or strange-quark stars; for quasiperiodic, well-known waveforms, such as the inspiral of neutron stars or black holes;
for bursts with poorly known waveforms, such as supernovae, gamma-ray burst progenitors, coalescences of neutron-stars to form black holes and for cosmic-string-generated bursts; for stochastic signals of cosmological or astrophysical origin. These searches can be targeted (such as for pulsars or gamma-ray bursts detected by electromagnetic astronomy) or untargeted.

Unfortunately, we have not detected gravitational waves in the first four science runs. We have been able to publish a series of improving observational upper limits [7] on a variety of gravitational-wave sources. Although there has been impressive progress in the range at which various sources could have been observed, the short duration of the first four science runs have prevented very strong limits on the rates of gravitational wave generation from being obtained. Since we have obtained our Initial Detector performance goals, we are now embarking on an extended run (S5) to significantly improve our ability to detect rare events. The S5 analysis will probe for compact binary inspirals and coalescences over clusters of galaxies; probe for neutron star ellipticities on the 10-7 scale; and establish an observational limit on the cosmological background of audio-frequency gravitational wave comparable to or better than the estimated “nucleosynthesis bound”.

5. Concluding remarks
There is today a worldwide network of gravitational-wave detectors that achieve noise-equivalent burst strain sensitivities from a few times $10^{-20}$ to below $10^{-21}$. This is a level of sensitivity that was hard to imagine a decade ago and these detectors continue to improve. There has been significant development toward a next generation of detectors, such Advanced LIGO in the US and LCGT in Japan, that promises a dramatic leap in range. By extending the volume of space searchable with the currently operating detectors by several hundredfold, this new detector generation should take world capability from the plausibility of detection to the establishment of regular observational astronomy using gravitational waves. New instrumental capabilities in electromagnetic astronomy promise very rapid progress in understanding the sources that generate powerful gravitational. This is a very exciting time to be in this field.

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References
[1] Thorne, K S 1987 *Three hundred years of gravitation* ed S W Hawking and W Israel (Cambridge: Cambridge University Press) chapter 9
Abramovici A et al 1992 *Science* **256** 325–33
[2] Regehr M W, Raab F J and Whitcomb S E 1995 *Opt. Lett.* **20** 1507–9
Flaminio R and Heitman H 1996 *Phys. Lett.* A **214** 112–22
[3] Abbott B et al 2004 *Nucl. Instrum. Meth.* A **517** 154-79
[4] Acernese F et al 2004 *Class. Quant. Grav.* **21** S385
[5] Willke B et al 2004 *Class. Quant. Grav.* **21** S417
[6] Takahashi R 2004 *Class. Quant. Grav.* **21** S403
[7] [http://www.ligo.org/results/](http://www.ligo.org/results/) has an updated listing of analysis papers from LIGO