Gravitational Wave Detection by Laser Interferometry on Earth

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Abstract

The existence of gravitational waves is the most prominent of Einstein's predictions that has not yet been directly verified. Worldwide, ground-based gravitational wave detectors using laser interferometry are being commissioned for science runs. The largest are the two US detectors of the LIGO project: facilities at widely separated sites in the states of Washington and Louisiana, each with 4 km armlength. LIGO data runs have shown the excellent reliability. Similarly encouraging results are reported from the British-German project GEO 600 with 600 m arms. The Japanese project TAMA 300 (with 300 m arms) was the earliest to exhibit good and reliable continuous runs. In all of these projects, the final level of sensitivity has yet to be attained. The French-Italian VIRGO project is to start using its 3 km interferometer by the end of this year. Future enhanced versions are being planned, with scientific data not expected until 2008.

The sensitivities to be obtained will allow cosmic events of great scientific interest to be monitored. Detection of the events, and the quantitative analysis together with the location in the sky will provide vital information not obtainable via the window of electromagnetic radiation.

1. Introduction

A new window in astronomic observation is presently being opened: the detection and measurement of gravitational waves (GW). This is one of the great challenges to modern physics. Although predicted by Einstein in 1916, a direct observation of these waves has yet to be accomplished. Great hopes of such detection lie in the ground-based laser-interferometric detectors currently nearing completion. These ground-based detectors are sensitive in the 'audio' frequencies: towards low frequencies, ground-based detection is limited by seismic noise, and yet more fundamentally by 'gravity gradient noise', the Newtonian attraction by moving masses, and thus they cover a range starting from a few Hz to a few kHz.

This is the first of three intended talks on GW detection by interferometry: on Earth, in Space (LISA), and an ultra-low frequency space project ASTROD, all three covered in a recent more detailed paper [1].

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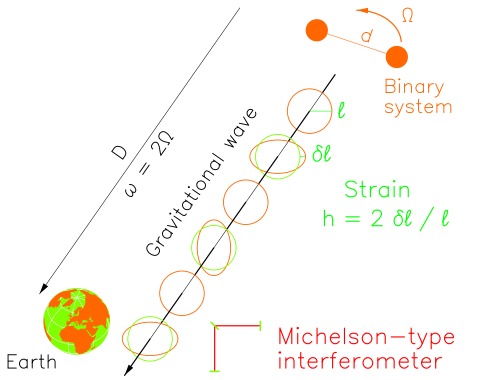

Fig. 1. Generation and propagation of a gravitational wave emitted by a binary system.

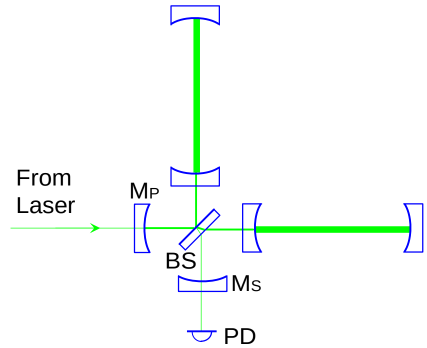

Fig. 2. Advanced Michelson interferometer with Fabry-Perots in the arms and extra mirrors M_P, M_S for power and signal recycling.

Gravitational waves (GW) have very little interaction with the measuring device, and in order to detect and measure these gravitational waves, we will require the most advanced technologies in optics, lasers, and interferometry.

Gravitational waves of measurable strengths are emitted only when large cosmic masses undergo strong accelerations, for instance – as shown schematically in Figure 1 – in the orbits of a (close) binary system. The effect of such a gravitational wave is an apparent strain in space, transverse to the direction of propagation, that makes distances ℓ between test bodies shrink and expand by small amounts $\delta\ell$, at twice the orbital frequency: $\omega = 2\,\Omega$. The strength of the gravitational wave, its dimensionless "amplitude", is generally expressed by $h = 2\,\delta\ell/\ell$. An interferometer of the Michelson type, typically consisting of two orthogonal arms, is an ideal instrument to register such differential strains in space. The difficulty in detecting them lies in the the smallness of the effect.

The perhaps most promising source of strong GWs is such an in-spiral of a neutron star binary. Out at the Virgo cluster (a cluster of about 2000 galaxies, $D \sim 14\,\mathrm{Mpc}$ away), we could expect a strain of order $h \approx 10^{-22}$. Similar (or even lower) strengths might be expected from supernovae out at Virgo cluster distances. That we insert such a large distance as the Virgo cluster is to have a reasonable rate of a few events per year, in our galaxy only a few per century.

So we have to measure – in a Michelson interferometer of kilometer dimensions – path changes in the order of $10^{-19}\,\mathrm{m}$. That this is not hopeless is shown by the encouraging sensitivities obtained in first science runs.

2. Ground-based interferometers

The underlying concept of all ground-based detectors is the Michelson interferometer (see schematic in Figure 2) in which an incoming laser beam is divided into two beams travelling along different (perpendicular) arms. On their return, these two beams are recombined, and their interference (measured with a photodiode PD) will depend on the difference in the GW effects that the two beams have experienced.

The changes δL in optical path become the larger the longer the optical paths L are made, optimally about half the wavelength of the gravitational wave: e.g. to 150 km for a 1 kHz signal. Schemes were devised to make the optical path L significantly longer than the geometrical arm length ℓ, which is limited on Earth to only a few km. The standard scheme is to use Fabry-Perot cavities (Figure 2), thus increasing the interaction time of the light beam with the gravitational wave.

After pioneering work by Rai Weiss at MIT (1972), other groups at Munich/Garching, at Glasgow, then Caltech, Paris/Orsay, Pisa, and later in Japan and Australia, also entered the scene. Their prototypes ranged from a few meters up to 30, 40, and even 100 m. Even though some of these prototypes reached the sensitivities of cryogenic resonant-mass antennas, they were never meant to be used as detectors, but rather as test-beds for verifying new schemes and configurations devised to overcome otherwise limiting noise effects.

The following list gives an impression of the wide international scope of the interferometer efforts, listed according to size of detector.

LIGO The largest is the US project LIGO [2]. It comprises *two* facilities at two widely separated sites, in the states of Washington and Louisiana. Both will house a 4 km interferometer, Hanford an additional 2 km one.

VIRGO Next in size (3 km) is the French-Italian project VIRGO [3], being built near Pisa. An elaborate seismic isolation system, with six-stage pendulums will allow measurement down to GW frequencies of 10 Hz or even below.

GEO 600 The detector of the British-German collaboration, GEO 600 [4], with a length of 600 m, has successfully participated in the LIGO science runs. GEO 600 will employ the advanced optical technique of "signal recycling" to make up for the shorter arms, a scheme later to be used in upgrades of LIGO.

TAMA 300 In Japan, on a site at the National Astronomical Observatory in Tokyo, the detector TAMA 300 [5] with 300 m armlength has made the earliest and longest data runs, exhibiting encouragingly long in-lock duty cycles.

2.1. Common data runs

For the received signal to be meaningful, coincident recordings from at least two detectors at well-separated sites are essential. A minimum of three detectors (at three different sites) is required to locate the position of the source, and only with at least four detectors can we speak of a veritable GW *astronomy*.

At the turn of the year 2001/2002, a first common data run between all three LIGO detectors and GEO 600 (and partly also TAMA 300) was undertaken, consisting of 17 days of mostly uninterrupted operation. This common effort exhibited encouraging duty cycles of the interferometers being locked, up to 95 %.

With the detectors not yet being at the intended sensitivity level, the aim was not a search for gravitational waves, but rather to rehearse the activities of data acquisition, data exchange, and of data analysis. A second such data run, S 1, between LIGO and GEO 600 was carried out in September 2002, yet another (S 2) without GEO participation from mid-February to mid-April, 2003.

2.2. Next-generation ground-based detectors

Even though the current detectors are not yet in full operation, it is essential to develop a next generation of detectors early on. Three plans for such next-generation detectors have been put forward, which will be sketched below.

Advanced LIGO Among these, the proposed US project is furthest progressed and well documented [6].

It will use the facilities at Hanford and Livingston: no cost for new sites, for civil and vacuum engineering, but it does not allow the incorporation of more "aggressive" approaches (cryogenics, all-refractive optics, Sagnac), and the option of the lower seismic noise of underground sites.

LCGT The concept of the Japanese project "Large Cryogenic Gravitational-Wave Telescope" (LCGT) is also rather well defined; it will use super-cooled (cryogenic) mirrors. The location of LCGT will be deep inside the mountain that houses the famous neutrino detector Super-Kamiokande. The ground noise is by nearly two orders of magnitude lower than at ground level.

EURO The funding agencies (CNRS, MPG, INFN, PPARC) of France, Germany, Italy, and the UK, agreed to pursue the definition of a common European high-sensitivity detector, EURO. However, the completion and the commissioning of the current projects, GEO 600 and VIRGO, has the highest priority.

3. Conclusion

The great challenge of gravitational wave detection stems from the fact that gravitational waves have so little interaction with matter (and space), and thus also with the measuring apparatus. And yet – just on account of their weak interaction – gravitational waves can give us knowledge about cosmic events to which the electromagnetic window will be closed forever.

References

1. A. Rüdiger, Int. J. of Modern Physics D **11** (2002) 963–994
2. D. Sigg, Class. Quantum Grav. **19** (2002) 1429–36
3. F. Acernese et al., Class. Quantum Grav. **19** (2002) 1421–28
4. B. Willke, Class. Quantum Grav. **19** (2002), 1377–88
5. M. Ando et al., Class. Quantum Grav. **19** (2002) 1409–1420
6. LIGO Laboratory document M000352-00-M (Dec 2000) 117–162.