Turn up the bass! Low-frequency performance improvement of seismic attenuation systems and vibration sensors for next generation gravitational wave detectors.

I think it is a great privilege to write a PhD thesis during this period in the field of gravitational waves. On these few pages I would like to summarize what has been going on in these past few years. First, I describe and discuss the grand results of the LIGO-Virgo Collaboration and how these results have been measured. Then I zoom in on the research done during my PhD.

Gravitational waves, listening to our Universe

The first detections of gravitational radiation have been a breakthrough in physics and astronomy. Just as the invention of the telescope ushered in a new era of discovery and understanding of the Universe, gravitational wave astronomy is expected to do the same. GW150914, GW151222, GW170104, GW170608, GW170814 and GW170817 (GW is the acronym for gravitational waves and the six numbers point to the detection day in year - month - day format) have shown us that (binary) black holes and neutron stars can be studied for the first time using gravitational waves. What is truly monumental about these first detections we can see the Universe in an entirely new way. Mankind's novel ability to directly detect gravitational waves is comparable to being deaf and suddenly gaining the ability to hear. An entirely new realm of information is now available.

The measured binary systems have collided hundreds of millions to several billion years ago after a very long dance around each other. The waves the systems emitted
have traveled to up until now to arrive here on Earth. When some of the measured waves began their journey, multi-cellular life began developing here on Earth. This life evolved to the human species. Within humanity, a genius emerged and predicted a hundred years ago that gravitational waves exist. This genius, called Albert Einstein, thought that the minuscule effect of these waves on Earth would never be measured. Even if they are real - he doubted several times whether they were not just a mathematical artifact - he deemed it technically impossible to measure the tiny effects. About 50 years ago, scientists have began trying to measure it anyway and ultimately built detectors that measured these waves at the end of their cosmic journey.

**Figure S.1:** A new look on the Universe’s black hole and neutron star population. X-ray studies have accumulated a family of black holes (purple spheres) below 20 solar masses. Our gravitational wave detections prove there are also heavier families out there (blue spheres). It is unknown what the product of the first neutron star merger we measured is: a light black hole or a heavy neutron star? Credit: LIGO/Virgo/Northwestern/Frank Elavsky.

**Implications of the first detections**

The first discoveries have shed light on our understanding of the dark Universe. Black holes had never been measured directly before, let alone a merger of two of these pure
space-time objects. The measurements, over more than 23 orders of magnitude, are the most precise distance measurements ever performed. This accuracy is comparable to measuring the distance from here to the nearest star outside the solar system (Alpha Centauri, 4.32 light years away) with the precision of the width of a human hair.

The first GW150914 discovery showed us that 3 solar masses of energy could vanish into space-time perturbations traveling at the speed of light. This was the single most powerful event ever measured, clocking in at 50 times the radiative power of the entire visible Universe at peak luminosity. The black holes involved, weighing about 30 and 35 solar mass each, are the heaviest stellar mass black holes measured to date. That such heavy black hole binary systems existed was new to astronomy as well, as shown in Fig. S.1.

The study of General Relativity, i.e. gravity, can now be brought up to a whole new level, the so-called strong field regime. With these new measurements data analysts can further constrain certain parameters in which they hope to find a hint where the theory of General Relativity - the description of macroscopic things - can be unified with the theory of Quantum Mechanics - the description of microscopic things. This envisioned merger of theories is one of the modern holy grails of physics.

![Figure S.2: Night sky localization of all gravitational waves detections by Advanced LIGO (GW150914, GW151226 and GW170104) and with Advanced Virgo (GW170814 and GW170817) done by the LIGO Virgo Collaboration. Credit: LIGO/Virgo/ NASA/ Leo Singer/ Alex Mellenger.](image-url)

The first few detections have been done with two LIGO detectors. With two detectors, you can get a ring of potential source positions in the sky from the timing differences. Out of the signal strength differences between the two detectors because they are on a different plane - the LIGO detectors are on opposite sides of the United States and the Earth is round - that ring can break a bit, but an area hundreds of times larger than the moon in the night sky is typical. With the addition of the European Virgo detector you see this area shrink dramatically, especially if it is a strong signal. This opens up possibilities for so-called multi-messenger astronomy, i.e. a complementary measurement of electromagnetic and gravitational waves. For GW170814 we already saw the area shrink and, three days later, GW170817 was detected and determined to be coming from a fusion of two neutron stars. The precise localization by the three gravitational wave detectors, shown in Fig. S.2 helped conventional astronomers to find an afterglow of this massive collision. In the afterglow, we were able to see for the first time the theorized process now known to be responsible for the abundance of elements heavier than iron in
the Universe, such as gold, platinum and uranium!

**How do you measure gravitational waves?**

Because there is a correlation between space-time and gravitational curvature, a gravitational wave will change the way objects *fall* with respect to each other. When a gravitational wave passes two objects, a measurable effect will occur. The physical distance between the two objects will stretch and contract as long as the gravitational wave is passing by. Gravitational waves are measured by accurately monitoring the position and movement of so-called test masses. To do exactly this, interferometers are used; they are kilometer-long laser set-ups with all kinds of optical elements such as a semi-reflective mirror (the so-called beamsplitter), a very powerful laser (typically hundreds of Watt) and highly reflective mirrors, which in this case are silicon cylinders weighing tens of kilograms. The beamsplitter and mirrors act as test masses and the distance between them is monitored to dazzling precision.

The basic principle is relatively easy to explain. A laser shoots a beam of light to for example the east through a beam splitter and 50% of the light continues its path due east into one of the interferometer arms. The other 50% reflects to a path an angle of 90° with the other beam to the north into the other interferometer arm. Both beams meet a highly reflective mirror at the end of their respective arm and reflect back to the beam splitter. The beams return at the beamsplitter, meet and, if both arms are equally long, they extinguish each other in the southern direction where there is a photo-detector; all the light goes back west to the laser. This is the result of (destructive) interference; the light waves are in anti-phase with each other and the result is no light at the photo-detector. When a gravitational wave passes, both arms will stretch and contract in anti-phase. This causes the interference effect to have a different outcome because the waves do not extinguish each other anymore completely. Little flashes of light are now detected at the photo-detector and tell us the distances between test masses are changing.

All gravitational wave detectors would measure nothing but seismic noise without all the elements of a detector being isolated from the ever-present minuscule vibrations of the Earth. These vibrations are typically one hundred billion (!) times larger than the effects of gravitational waves. To suppress the vibrations, we work with harmonic oscillators. To quickly understand what a harmonic oscillator is in this context, imagine an unrolled yo-yo (or take it out of your drawer!). Hold the yo-yo at the end of the string. Your hand is the vibration you want to suppress - for example the Earth’s vibrations - and the yo-yo is the mirror. If you slowly move your hand back and forth, there is no suppression of the vibrations; the yo-yo moves as much as your hand. There is a speed of back-and-forth hand motion (or frequency) where you get lots of yo-yo motion; this is called the resonance frequency and there is vibration amplification at that frequency. This is the price we have to pay for the behavior of the system above the resonance frequency. Now move your hand quickly back and forth and you see that the yo-yo is not following; above the resonant frequency there is vibration suppression.
We mitigate the price we have to pay - the amplification at the resonance frequency - with control technology; sensors measure the movement and a computer tells actuators - typically a magnet and an electrical coil - when a (small) force needs to be sent to the system - the yo-yo in our example - to damp the amplification at the resonance frequency. You can imagine that these control systems are running continuously to keep those huge interferometers, in practice a complex optical arrangement with dozens of suspended mirrors, aligned during the measurements. In a typical gravitational wave detector, there are hundreds of so-called feedback loops that keep an eye on everything.

Since the nineties, a lot of work has been done to set up a global network. The two LIGO detectors in Hanford, Washington and Livingston, Louisiana in the United States of America and the Virgo detector near Pisa, Italy are already operational. KAGRA, an underground detector in Japan (from 2020 onwards) and LIGO India (from 2022 onwards) will strengthen the network. So will new future detectors designed to exceed the sensitivity of the present detectors. The so-called Einstein Telescope in Europe and the Cosmic Explorer in the United States are expected to be realized in the third decade of this century. With more sensitive detectors we can not only crank up the amount of detections per year, but also look (back) further into the Universe.

In Advanced Virgo, there are now tables on which optics perform measurements to better align the main mirrors. These optical tables have to be isolated from the Earth's vibrations. To this end, compact seismic isolation systems have been developed at the National Institute of Subatomic Physics Nikhef. This dissertation describes that seismic isolation system for the optical tables (chapter 3), a new vibration sensor to better monitor the performance of seismic isolators (chapter 4) and the author's work on similar aspects of the KAGRA gravitational wave detector done during three visits to Japan (chapter 5).

**Compact seismic attenuation system**

The system that suspends the optical tables in Advanced Virgo is called MultiSAS. In the prototype phase (2011 to 2014), Nikhef engineers learned a lot about the mechanical modes of the system with so-called finite element (FEM) and state space models. This resulted in minimal design adjustments and the installation of several different damping strategies. The performance measurements of MultiSAS have not shown any surprises. Following this prototype campaign, five systems were constructed to be installed in Advanced Virgo. The systems behave according to expectations and meet the requirements set by the Advanced Virgo design.

All systems were installed and tested with a dummy mass. After this 2014 campaign, the dummy masses were removed and the MultiSASs were ready to suspend the tables. In the run-up to observation run 2 (O2), all control filters were designed and there were also some other tests done. Examples of these tests are determining if construction tolerances were not detrimental to MultiSAS performance, tests on thermal shielding of certain delicate parts of the mechanics, and determining the maximum pressure allowed
in the vacuum envelope around MultiSAS in which acoustic effects are not yet visible. Four out of five systems suspended an optical table in O2. SIB2, the injection system suspended bench, is also ready for suspending its optical table, but this was not yet necessary in O2. The remaining four systems, called SNEB, SWEB, SPRB and SDB2, isolate critical optical components for linear and angular alignment. SDB2 - suspended detection bench 2 - also houses the photodiode that captured the GW170814 and GW170817 signals at the end of O2!

The prototype MultiSAS is now used in an advanced sensor and control test bed at Nikhef. MEMS accelerometers and our vibration sensor with interferometric readout are developed on the seismically isolated table. A vibrationally quiet optical table is now also available in Amsterdam for companies outside academia to test sensors.

![Image](image.png)

**Figure S.3:** Femtometer precision achieved with Nikhef’s new vibration sensor. Compared to the Sercel L4C geophone (both measurement and specification) and the GeoTech GS13 (specification of the world’s best commercially available vibration sensor), this sensor gives access to vibration measurements of a few millionths of billionths of meters (femtometers, new area is shaded green). The purpose of the sensor is to measure even more accurately the vibrationally quiet locations we create with our seismic isolators.

### Interferometric readout of a vibration sensor

Optical tables suspended by MultiSAS are so quiet that the best commercial sensors only measure self-noise from about 5 Hz onwards. Nikhef has proposed a combination of two proven ideas into a vibration sensor with unprecedented sensitivity. Such a sensor is needed to better monitor the motion of a vibrationally isolated object. This vibration sensor has been tested in the MultiSAS test facility and has a self-noise level of 8 fm/√Hz from 30 Hz onwards, which as shown in Fig. S.3 is a factor ten more sensitive than the world’s best commercial sensor at 30 Hz.
Additionally, the same interferometric readout has been realized using fiber optic. This readout achieved a preliminary sensitivity of $4 \text{ pm/} \sqrt{\text{Hz}}$ from 5 Hz onwards. The next step is to install this sensor on the MultiSAS optical table in vacuum. The advantage of using fiber optic is that electrical components do not have to be near the sensor mechanics. Such a sensor can thus be installed in radiation or high magnetic field environments, such as in next generation particle accelerators. The readout could even be used as an independent displacement sensor, e.g. for the main mirrors of our detectors.

**Controls for KAGRA’s suspension systems**

The author has visited Japan as part of the ELiTES exchange program during the development and construction phase of the KAGRA gravitational wave detector. At NAOJ (Mitaka, Tokyo) development and testing of controls has been performed on the last stage of so-called Type B(p) vibration suppression systems. The performance of that subsystem is within the requirements of the KAGRA design. Work has been done to improve the sensor part of the OSEM, the combined sensor and actuator used in KAGRA. The sensing part consists of a so-called shadow sensor and requires a light beam that is as homogeneous as possible. Testing all sorts of different LEDs and collimator lenses has improved the design which will ultimately be used in KAGRA.

At the KAGRA site, the first stage of the seismic isolation systems for the main detector elements is a so-called inverted pendulum stage. These systems - designed, assembled and tested at Nikhef - have a very low resonance frequency ($< 0.1$ Hz), with the goal of suppressing the microseismic motions of the Earth caused by oceanic activity. Simulations to determine which sensor can be used best to achieve this goal have been performed. The next step is to physically measure the motion predicted by the simulations and decide which sensor to use.

The future of gravitational wave astronomy is bright, or should one say loud?! Hearing the sounds of the dark Universe, after centuries of being deaf, is a blessing for astronomy. New discoveries and further tests of Einstein’s theory of General Relativity are expected. Stay tuned!