General relativity describes gravity as the curvature of spacetime, with the properties of the curvature contained in the metric. Gravitational waves are fluctuations in the spacetime continuum and are represented by perturbations of the metric. They propagate at the speed of light and are one of the last predictions of general relativity yet to be validated. The emission of gravitational waves follows from any object that exhibits a quadrupole (or higher order) moment. Since the fabric of spacetime is extremely stiff, the first detectable gravitational wave signals are expected to originate from events of astronomical proportions. Sources such as supernovae gravitational core collapse, spinning neutron stars and binary mergers were described in Chapter 1. It was established that signals below roughly 40 Hz, the low-frequency regime of ground based detectors, are of great importance. This is due to the many potential sources of gravitational waves that exists at these frequencies, such as spinning neutron stars and binary black hole mergers. Furthermore, the time to coalescence of binary mergers increases with \( f^{-\frac{8}{5}} \) which means that a lower detection frequency improves the signal-to-noise ratio and subsequent parameter estimation of these events.

Gravitational waves can be detected by closely monitoring the separation distance between freely falling test masses. This is done with kilometer scale interferometric detectors, like Virgo in Italy, where the mirrors act as freely suspended test masses. Virgo is currently being upgraded to what is known as a second generation detector coined Advanced Virgo. Together with a global network of a handful of other second generation detectors, sensitivities ten times better than first generation instruments will be reached and gravitational wave detections are expected from 2016. Looking onwards, future generation detectors such as Einstein Telescope are in a mature phase of conceptual design. Einstein Telescope will improve on second generation sensitivity by another order of magnitude and pushes the lower bound of the detection band to even lower frequencies.

The limitations of ground based detectors lie in sources of quantum noise (from shot noise and radiation pressure), thermal noise and noises associated with seismic motion. The latter appears as mechanical transmission through the suspension systems of the
Chapter 7. Conclusions, discussions and future work

optical components, or via the direct Newtonian coupling due to density fluctuations from seismic waves. In addition, technical noises such as angular alignment control noise necessitates the use of vibration attenuation systems to isolate optical benches from seismic vibrations.

Seismic noise

Seismic noise (and associated Newtonian noise) plays a major role in limiting low-frequency performance of ground based detectors from 1 Hz, up to 6 Hz for Einstein Telescope and up to 20 Hz for Advanced detectors. At 1 Hz there was evidence of the tail of the microseismic peak, a result of ocean activity coupling to seismic motion that has its maximum amplitude around 0.2 Hz. It was shown with data from a European seismometer network (VEBSN), that at these frequencies there exists a relation to a site’s proximity to the North Atlantic ocean. Above 1 Hz it was shown that seismic motion originates from anthropogenic sources, such as traffic, industry and other human activity. For this reason, future sites should avoid highly populated and industrious areas. Furthermore, the energy from these sources was shown to couple largely to surface waves that decay with $1/\sqrt{r}$, with $r$ the distance from the source. In contrast, the remaining energy is distributed among body waves that decay as $1/r$. This motivates the notion of constructing a future detector underground.

A global campaign to characterize underground seismic motion in conjunction with the Einstein Telescope design study was carried out. It showed that significant improvements of the seismic environment could be obtained by careful site selection. A number of locations in Europe show several orders of magnitude reduction in seismic power spectral density in comparison to current detector sites. Some sites were shown to exhibit reduced seismic motion at greater depth, however surface sites also exist that provide low seismic activity. These studies conclude by specifying a realistic seismic noise requirement for Einstein Telescope that corresponds to an average displacement amplitude spectral density no greater than $0.5 \text{ nm/} \sqrt{\text{Hz}} (\text{Hz}/f)^2$ above 1 Hz.

Three underground and one surface location were proposed as potential sites for further investigation. Subsequent studies will identify the long term seismic characteristics of these or similar environments. Another important aspect that will need to be addressed for a subterranean detector is the feasibility of large underground construction. At the surface site the focus could lie more on the study of the effects of atmospheric conditions, such as wind, and the feasibility of a future generation surface detector.

Chapter 3 concluded by describing a study of seismic correlations performed at the Virgo site. This provided information on the typical coherence length of seismic motion as a function of frequency. From these results it was also possible to generate an estimate of the surface wave velocity and soil density. Both were useful in modeling the Newtonian noise contributions to the Advanced Virgo noise budget. A more detailed seismic correlation study at the Virgo site would be useful. Such a study should involve
longer measurement periods at various separation distances including locations along
Virgo’s North arm. This will provide a more accurate description of the site’s dispersion
properties and soil density profile.
Seismic noise for next generation detectors can be summarized as:

- Frequency range of interest: > 1 Hz up to 6 Hz for Einstein Telescope and up to
  20 Hz for advanced detectors.
- Generally originates from anthropogenic sources at the surface (roads, industry,
  human activity).
- Rayleigh waves contain roughly two thirds of the excitation energy, and decay as
  $1/\sqrt{r}$, as opposed to one third of the energy and $1/r$ decay for body waves.
- Future generation detector sites should therefore avoid highly populated and indus-
  trial areas and consider underground locations.
- Reductions of several orders of magnitude in seismic power spectral density is achiev-
  able with respect to current detectors sites.
- A realistic background seismic noise requirement for Einstein Telescope is set to
  $0.5 \text{nm}/\sqrt{\text{Hz (Hz/f)}}$ above 1 Hz.

Newtonian noise

Newtonian noise will limit the low frequency sensitivity of advanced detectors during
high seismic activity and will be a dominant limitation to Einstein Telescope’s perform-
ance below 6 Hz. New methods to model Newtonian noise were presented for two
categories of seismic wave sources: distant sources, numerically modeled by isotropic
plane Rayleigh waves; and local sources for which finite element techniques were relied
upon.
Results from plane Rayleigh wave models showed dependence on seismic correlation:
weaker correlation produces more areas of incoherently vibrating soil, the effects of
which cancel each other out in the Newtonian noise integration process. This was evi-
dent in simulations of two different soils properties: that of the Virgo site with low
 correlate; and the higher correlated properties of those found, for example, at SLAC,
Paolo Alto, USA. The results also presented the idea of Newtonian noise reduction as
a function of depth. At lower frequencies, Rayleigh waves penetrate to greater depths,
and the seismic motion is correlated over greater distances. Therefore, the reduction in-
creases with increasing depth and frequency. However, at 1 Hz, a depth of one Rayleigh
wavelength is needed to achieve an order of magnitude suppression, which corresponds
to unfeasibly large depths for an underground detector. At 3 Hz this is already reduced
to roughly a quarter of that depth. This is due to the shorter penetration depths and
the stronger Newtonian integration cancelation effects at higher frequencies.
In the case of Advanced Virgo, simulations were made based on seismic noise, soil density
and dispersive properties measured at the site. This led to results that diverged from current Newtonian noise models which do not take dispersion into account. Due to the lower correlation associated with the dispersive properties, simulations produced lower estimates of Newtonian noise, by roughly an order of magnitude in the 10 - 20 Hz band. As a result, it is proposed that the Rayleigh wave contribution to the Advanced Virgo Newtonian noise budget be adjusted to coincide with a density of $\rho = 1.8 \text{ g/cm}^3$, and a reduced transfer function $\beta = 0.25$. Even in this case, Newtonian noise will still limit Advanced Virgo's sensitivity below 20 Hz during high seismic activity.

The above simulations modeled surface Rayleigh waves only. At a surface detector such as Advanced Virgo it is expected, and indeed shown in Chapter 3, that surface waves will be the dominant source of seismic motion. At underground sites however, where the effects of surface wave motion are reduced, body waves will dominate. The models can be extended to include body waves from distant sources to further improve our understanding of underground Newtonian noise issues.

Finite element models were shown to accurately predict the seismic wave fields from point source excitations at the surface of a homogenous half-space. These included all wave types: body and surface. Subsequent Newtonian noise simulations with virtual test masses at the surface and at depth, showed that Newtonian noise was felt immediately, before any seismic motion was detected at the respective locations. In addition, there was only a small reduction in Newtonian noise signal with depth, suggesting that body wave contributions from these sources will be significant, even at large depths. The strength of finite element simulations is their ability to model complex structures and excitations. This would make it suitable to study more complex geologies, such as layered media, or the effects of buildings and topological structures close to the test masses. However, high resolution sampling of the seismic wave fields together with sufficiently large models make it computationally challenging.

Finally, subtraction of Newtonian noise from ambient seismic motion at a surface detector, based on arrays of seismic sensors and an optimal Wiener filtering technique was presented. Simulations were made by using the plane Rayleigh wave model and showed that over 90% of the signal could be subtracted with an array of several hundred sensors. Even better results could be obtained by carefully selecting the optimal positions of the sensors. However, this placement strategy optimizes the array within a chosen narrow bandwidth, while a broadband solution may be needed. The technique does provide valuable insights into a semi-optimal configuration of the sensor array. Based on the results an hourglass arrangement aligned parallel to the interferometer arm is proposed and should feature with a higher density of sensors closer to the test mass. The extension of these simulations to three dimensional arrays and underground detectors would be valuable for assessing the feasibility of Newtonian noise subtraction for future generation detectors, such as Einstein Telescope.

Newtonian noise for next generation detectors can be summarized as:
• **Distant sources**
  - Originate at a distance $d \gg \lambda_P$ from the test mass.
  - Predominately from Rayleigh waves at the surface.
  - Modeled by isotropic plane Rayleigh waves with measured dispersion properties.
  - Dependent on seismic correlations due to integration over coherently vibrating areas of soil.
  - Low frequency $\lesssim 2$ Hz
    - Long coherence lengths.
    - Limited noise reduction as a function of depth.
    - Order of magnitude reduction at $z \approx \lambda_{R,1Hz}$.
    - Subtraction requires sparse seismic arrays over large distances.
  - High frequency $\geq 5$ Hz
    - Short coherence lengths. Stronger Newtonian integration cancelation effects.
    - Noise reduction as a function of depth.
    - Order of magnitude reduction at $z \approx 0.25\lambda_{R,1Hz}$.
    - Subtraction requires denser arrays in closer proximity to the test masses.

• **Local sources**
  - All wave types are produced by these sources.
  - Modeled with finite element methods.
  - Newtonian noise is immediately felt at test mass before corresponding seismic signals arrive.
  - Limited reduction as a function of depth: roughly a factor of 2 at $\lambda_{P,1Hz}$.
  - Body waves from surface sources are still dominant at depth.
  - Sources are generally known and controllable.

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**Vibration isolation**

A compact vibration isolation system called MultiSAS has been developed to suspend five of Advanced Virgo’s in-vacuum optical benches. Scattered light and alignment control issues place stringent requirements on the residual motion of the benches, particularly in the rotational degrees of freedom. MultiSAS implements multiple stages of mechanical filters in the form of (inverted) pendulums and geometric anti-springs, such that the bulk attenuation is obtained via passive isolation. The rigid body modes of the system are suppressed by an active feedback control system that acts in a bandwidth up to 5 Hz. Sensing is performed by a series of differential displacement sensors called LVDTS and inertial velocity sensors called geophones, while the feedback forces are applied via magnetic voice coil actuators.

MultiSAS is designed to provide 150 and 100 dB of attenuation of ground vibrations for frequencies above 10 Hz in the horizontal and vertical degrees of freedom respectively. In addition, the design is conceived to minimize couplings between translational and
rotational degrees of freedom. The vertical performance was demonstrated by actuated swept sine transfer function measurements and was well within the requirements for translational motion. More crucial is the performance of the rotational degrees of freedom. This will need to be tested once the MultiSAS prototype has been installed in the custom build vacuum enclosure, including the prototype optical bench.

Vertical and horizontal models of MultiSAS were developed based on Lagrange mechanics. These were shown, via comparison with measured transfer functions, to provide an accurate description of the system’s dynamics. Based on the vertical state-space model a Kalman filter was designed to observe the states of the system, including those that could not be measured. This meant that the signal measured by the LVDT at the top stage could be effectively blended with the geophone signal from the bench, to estimate the various system states. Furthermore, in combination with an optimal regulator a linear quadratic Gaussian feedback controller could be realized. This implementation of a multiple-input single-output controller was shown to reduce the residual rms motion of the bench well below the required 1 μm, a reduction in motion by more than an order of magnitude in comparison to the open loop motion.

Exciting times await MultiSAS in the immediate future. It will be installed in the MiniTower vacuum enclosure and its prototype optical bench will also be commissioned. In this configuration the system’s dynamics, including those of the MiniTower, can be further explored. The control strategies outlined here can be extended across more degrees of freedom and perhaps tuned for more optimal performance. Ultimately five such systems will be installed in Advanced Virgo with the first of these to be installed in the middle of 2014.