fields. This is the primary source of "seeing" noise that affects optical astronomy. Fluctuations occur at all length scales down to few millimeters, but have typical timescales much longer than a second. Therefore, associated NN would not affect ITF noise spectra above 1 Hz or so. Unless air volumes are displaced at some considerable speed past the interferometer, as occurs in presence of wind or air blowing. The gravitational coupling at frequency f depends on the factor $\alpha = 2\pi f r_{min}/v$, where v is the wind speed and r_{min} is the minimum distance from the test mass of the passing air-volume. In the simple case of smooth air flow the coupling has exponential an decay, $e^{-\alpha}$ [175]. In case of vortexes the suppression with distance is not exponential anymore, but coupling is negligible for distances larger than ≈ 100 m [97].

While underground detectors would be naturally shielded, the issue needs to be seriously evaluated in the case of surface detectors. Mitigation of density perturbation associated with humidity and temperature fields through cancellation schemes is ideally possible using LIDAR and Doppler LIDAR sensors to produce 3D maps of air temperature, humidity and velocity [178, 179].

11 Environmental noise considerations in site selection and site facilities

The experience gained from first and second generations of gravitational wave detectors may be useful for future generations of detectors. While some coupling mechanisms may differ, for example Newtonian noise may couple vibrations that, in earlier detectors, coupled through optic suspensions, the minimization of environmental noise will likely always be prudent. Below we briefly list some considerations, based on lessons learned, that may be helpful in site selection, and some considerations that may be helpful in minimizing self-inflicted noise from future facilities. Of course, not all of these considerations apply to underground facilities.

11.1 Site selection considerations for minimizing environmental noise

Environmental noise measurements for evaluating proposed sites should likely include seismic, acoustic (including infrasound), magnetic, and RF backgrounds. Measurements of frequency-dependent seismic propagation velocities and quality factors are also important, especially for surface waves. Long term measurements of background levels can be important, as sources of noise can be seasonal, such as wind, crop harvesting (and trucking), and the ocean-storm driven microseismic peak. In addition, the background measurements should focus on transient levels as well as average levels. Investigations of transients may require examination of noise amplitude spectral density on multiple time scales so that short transients, such as 0.1 s transients from blasting, are not averaged with transient-free periods.

Prior to actual site measurements, candidate sites can be evaluated using information available on the internet and Google Earth. This includes most of the considerations in the list below:

1. Geology.
2. Microseismic peak level (minimize relative motion of detector stations, Section 6.3).
3. Wind speed distribution (minimize wind greater than about 10 m/s).
4. Expected weather changes associated with climate change.
5. Nearest train tracks and density of train traffic on those tracks (trains can produce 1-3 Hz seismic noise, especially within 20 km, and, if electric, can produce magnetic noise transients below 10 Hz especially less than 10 km away, Section 9.4).
6. Nearest highway, and truck traffic density (especially within 10 km; frequency, given by axle spacing and speed, is generally in the 4-15 Hz band; transient vibrations from trucks can be an order of magnitude worse than from cars, and at lower frequencies due to greater axle spacing [180]).
7. Nearest bridges and viaducts (including those for trains), which may have structural resonances that are excited by vehicles (see also Section 6.4).
8. Conditions of nearest roads (the largest 4-15 Hz seismic signal at a LIGO Hanford Observatory (LHO) end station was reduced by a factor of 2 to 3 when highway 240, 2 km away, was resurfaced [98]).
9. Nearest gravel or dirt road and traffic density (gravel and dirt roads typically produce much more vibration noise per vehicle than other roads).
10. Off-highway recreational vehicle activity within 10 km (the signal from variations in force against the ground is typically in the 3-15 Hz band).
11. Nearest activity involving heavy equipment, such as mining and quarrying (varying forces from massive vehicle motions can be more important than higher frequency activities such as rock crushing, because of greater attenuation of high frequencies).
12. Potential logging activities (also mainly due to variations in force from massive vehicles).
13. Nearest likely construction (again the worst sources tend to be massive earth moving equipment in motion, mainly within 20 km).
14. Nearest town (within 20 km).
15. Population density.
16. Nearest dam. LHO astrophysical range was limited at night during spring season high-water flow by 1-3 Hz vibration from water flow over McNary Dam, 60 km away) [91, 92].
17. Nearest power substation (mains current returning in the ground to a substation near the Ligo Livingston Observatory (LLO) travels on the grounded beamtube and produces magnetic glitches inside the buildings as stoves, heaters, etc. in Livingston turn on and off, Section 9.1).
18. Nearest trunk power line (some of the largest magnetic transients at LHO are produced by current fluctuations in a 500 kV, 700-3000 A transmission line about 2 km away [181]).

19. Does it share an electrical grid with another GW detector (unlikely, but may be a source of correlation between detectors)?
20. Is it on a heavily used flight path of a nearby airport (does it line up with a runway within about 50 km)?
21. Proximity to military training areas (LHO experiences 1-12 Hz seismic and acoustic transients from tank and artillery practice at the Yakima Training Center, about 50 km away [182]).
22. Proximity to potential wind farms (infrasound coupling to the ground may be important, Section 6.4).
23. Proximity to other facilities with large rotating equipment (cooling fans at a nuclear power plant 6 km from LHO produce seismic signals that are at least an order of magnitude above background at about 2 Hz [93]).

11.2 *Site facilities considerations for minimizing self-inflicted environmental noise*

The considerations in this section are associated with the non-technical facilities. Considerations associated with technical systems, such as vacuum, clean room, and electronics systems, are discussed elsewhere in this Chapter.

11.2.1 Buildings

1. Consider the most energy efficient, best insulated buildings possible in order to minimize global HVAC requirements: lesser energy usage is likely associated with lesser vibrational noise.
2. To minimize wind-induced floor tilt at wind gust frequencies, vacuum chamber supports should be far from the building walls (>5 m). Varying pressures on a building cause elastic dimpling of the ground near the wall supports (Section 6.3).
3. Metal clad buildings can be good at reducing external EM fields. But concrete buildings with well-grounded rebar can also be good Faraday cages at frequencies in the detection band, and up to frequencies given by the rebar spacing.
4. Concrete buildings are usually better at blocking sound and infrasound than metal clad structural steel buildings. Also, consider concrete construction around acoustic noise sources such as HVAC chillers.
5. Another advantage of concrete buildings over metal clad structural steel buildings is that the concrete buildings are likely to be more damped. Structural steel buildings, particularly in wind, can increase ground motion inside by more than an order of magnitude at their resonances, typically in the 2-10 Hz band.
6. Siding, flashing, and roofing, where present on sensitive buildings, should be rigid, well supported, and damped to minimize acoustic noise in wind and rain, especially any large regions that could buckle or "breathe" and produce infrasound inside when it is windy.

7. Low frequency acoustic modes may be damped by suspended ceilings and other techniques.
8. Consider designs that distance human activity (such as in control rooms, offices, labs and shops) from the vicinity of sensitive regions (i.e. experimental areas at interferometer vertexes).
9. Outlying buildings that do not house the interferometer should nevertheless be subjected to the vibrational considerations in Section 11.2.3 and Section 11.2.4 because low frequency vibrations attenuate little with distance (discussed below).

11.2.2 Site roads and parking areas

1. Vehicle movements on gravel and dirt generate much larger amplitude vibrations than on asphalt or concrete. There should be no gravel/dirt roads or parking lots near the buildings.
2. Gravel and sand located near the roads can contaminate the roads, making them generate larger seismic signals.
3. Shallow pipes under roads, road expansion joints, cattle guards etc. can make bumps that vehicles drive over, producing vibrational noise. Consider burying pipes and conduits at least 0.5 meters beneath the roads.
4. Consider selecting materials and construction methods that minimize cracking in the road surfaces with age.

11.2.3 Mains electrical considerations

1. Consider having mains building wiring twisted near sensitive regions in order to minimize magnetic fields at the mains frequency and magnetic field transients.
2. While it is general practice for electricians to run supply and return wiring in the same conduits, there have been occasions when they were run in separate conduits, leading to large loop areas and unnecessarily large magnetic fields.
3. It may be prudent to inspect high-current equipment installations for unnecessary current loops in the wiring, typically where an electrician connects the equipment to the mains.
4. Consider vibration isolation of the mains transformers that come with the building when they are near sensitive regions. This is occasionally done without special requests, though not as commonly as for equipment with moving parts. But mains transformers can be a strong source of vibrations (at even harmonics of the mains frequency). Acoustic isolation should also be considered.

11.2.4 HVAC and other equipment

1. Spring isolation of HVAC and other equipment (Section 7.2.2) can be very effective, but was sometimes shorted, especially by connected pipes and ducts, or simply installed improperly.
2. Vibration from turbulence in HVAC air and coolant lines can be worse than vibration from the actual fans or pumps, which are not broad-band and are easy to seismically isolate on springs.

   a. Coolant lines and air ducts with larger diameters reduce flow speed and turbulence.
   b. Variable frequency drives can be used to reduce chilled water flows and associated turbulence when demand is lower, if their EM noise is acceptable.
   c. HVAC fans, like turbines, with high speed air flows, produce turbulence at the output where speed changes rapidly. Screens over the turbine output can reduce low frequency turbulence [183]. But in general, lower air speeds, such as produced by "squirrel cage" fans, are preferable. If fans are in fan boxes, the boxes themselves should be isolated by placing them on springs.
   d. To reduce distance-associated resistance, and thus total energy in air and chilled water circuits (a fraction of which will inevitably drive vibrations), it may be preferable to locate HVACs nearby. LIGO and Virgo have been using banks of ductless small HVAC systems where extra cooling is needed, such as for electronics rooms (Section 7.2.2). The coolant pipes should be isolated. A drawback is that the external chiller units can be strong acoustic sources at fan frequencies. The electrical and vibrational disturbances at startup can be reduced with slow starts.

3. Underground equipment can couple strongly to the ground.

   a. Underground pipes with the potential to produce strong transients or turbulence, like HVAC chiller pipes, should not be in direct contact with the ground (elastic insulation may reduce coupling), or they should run above ground with vibration isolation.
   b. Underground motors (e.g. sump pumps and well pumps) should not be in direct contact with the ground and should be on springs like equipment on the surface.

4. The benefits of increasing the distance from a source depend strongly on the seismic wave frequency. Surface wave amplitude only drops geometrically as the square root of distance, until the frequency-dependent exponential attenuation term becomes important:

$$A_{far} = A_{near}\sqrt{\frac{R_{near}}{R_{far}}}e^{-\frac{\pi f}{Qv}(R_{far}-R_{near})}$$

   where f, v and A are the seismic wave frequency, velocity and amplitude; R_{near} and R_{far} are distances to near and far source options, respectively; Q is the seismic quality factor. For the sandy desert at LHO, the measured wave velocity is about 500 m/s at 5 Hz and 150 m/s at 60 Hz; Q is about 50 at 5 Hz. For the Virgo mud-clay surface soil, values of $v = 200$ m/s and $Q = 30$ have been measured at a few Hz. In general, seismic quality factors are between 20 and 200 and change slowly with frequency. The $1/e$ distance at LHO is about 40 m at 60 Hz, 150 m at 20 Hz, and 1600 m at 5 Hz.

5. Acoustic considerations.

   a. Ducts should usually be large diameter, double-walled, acoustic ducting. Watch for vibrating single-wall connector segments in double-walled systems, which can be very noisy.
   b. It is likely advantageous to place equipment with fans or other moving parts in separate rooms (possibly acoustically treated) from the vacuum chambers, in order to reduce acoustic coupling.

6. Considerations associated with heating and with temperature control.

   a. Electric heaters can be the largest current users in a building and produce the largest magnetic fields. Consider avoiding pulsed building heating (many systems use thyristors to pulse heater currents at about 1 Hz, and control temperature by varying the "on" time in each cycle) and avoiding other pulsed heating currents (in many chiller systems used for lasers). The pulsing transients produce combs in the magnetic spectrum around the mains frequency, with the individual peaks spaced by the pulse frequency (Section 9.1.2).
   b. Building heating elements can often be current loops with significant areas, and, because the heating currents are large, heating elements can be the most significant generators of magnetic field transients. It is possible to obtain special two-pass heating elements that minimize the loop area.
   c. Building temperature control sensors should be away from the walls and near (but not directly on) the vacuum chambers where temperature control is most important.

7. Considerations associated with motor and fan frequencies.

   a. In general, it helps to use higher frequency motors (2 pole instead of 4 or 6 pole motors) to take advantage of the fact that seismic attenuation is typically greater at higher frequencies.
   b. Reciprocating compressors should probably be avoided in favor of scroll or other designs.
   c. If possible, designed mechanical resonances of sensitive components should be away from motor frequencies (for 60 Hz mains, 58-60, 28-30, 17-20, and 14-15 Hz) in order to minimize problems with 2, 4, 6 and the occasional 8 pole motors, respectively.
   d. Variable speed fans and motors, in HVACs and in other systems, can be problematic because they affect a larger portion of the spectrum than constant frequency systems, and are thus more likely to excite resonances. Variable fre-

quency systems are now almost ubiquitous because of energy savings. However, some variable frequency equipment can be set to maintain constant frequency because frequency variation can be annoying to nearby people. These more versatile systems may be preferable.

8. Considerations associated with control and monitoring.
    a. Consider HVAC control systems that can be easily modified, both LIGO and Virgo have needed to modify their HVAC control systems.
    b. The ability to easily monitor the state of heaters, chillers, fans, air flows etc., and correlate them with detector channels has been expanded at both Virgo and LIGO and is probably essential (Section 4.1.3).

12 Conclusions

Over the next decade, the network of ground based GW detectors will go through phases of upgrades in which the sensitivity will be improved followed by observing runs in which the detection of numerous gravitational wave sources is expected. On longer time scale, the Einstein Telescope will be the first underground GW detector in Europe, while Cosmic Explorer will be a 40 km long interferometer in the U.S. They will be at least one order of magnitude more sensitive than the current detectors and will extend the observation band down to approximately 1 Hz.

Environmental disturbances will continue to be a main subject of investigation. It will be necessary to ensure effective noise monitoring through an widespread array of well positioned sensors.
It will be important to make an accurate and periodic measurement of the coupling of ambient noise to the detector. This information is essential for the GW event validation, and to produce an online budget of the contribution of environmental noise to the interferometer in order to promptly identify the appearance of new noise or worsening in the noise coupling. A useful effort is the further automation of these measurements. Also important is the development of additional effective tools for the noise analysis and experimental investigation, particularly in the field of non-linear processes and scattered light.

The experience collected in facing known and unexpected noise teaches the importance of tacking environmental noise in the detector design phase to reduce noise emissions, cut down transmission paths and reduce couplings.
As illustrated through the sections of this Chapter, some issues require special attention in the next generation of ground based detectors. One issue concerns the anthropogenic noise. It can be reduced in underground laboratories, but the implementation of a low-noise and monitored detector infrastructure is crucial in order not to undermine the advantages of going underground.
Particular attention must be paid to low frequency seismic and acoustic noise sources. In fact, the noise band up to a few tens of Hz can become relevant for Newtonian noise. Therefore, it is important to make a careful choice of the detector