Tunnel configurations and seismic isolation optimization in underground gravitational wave detectors.

DRAFT

Florian Amann[1], Francesca Badaracco[2], Riccardo DeSalvo[3], Andrea Paoli[4], Luca Paoli[4], Paolo Ruggi[4], Stefano Selleri[5]

1 Engineering Geology, RWTH Aachen, Lochnerstrasse 4-20 D-52064 Aachen, Germany

2 Centre for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, Louvain-La-Neuve, B-1348, Belgium

3 University of Utah, Dep.t of Physics & Astronomy, 115 South 1400 East 0830 Salt-Lake-City UT 84112 (USA),

Università del Sannio, C.so Garibaldi 107, Benevento, I 82100 (Italy),

Riclab LLC, 1650 Casa Grande Street, Pasadena, CA 91104 (USA)

4 EGO, European Gravitational Observatory, Via Edoardo Amaldi,556021 Cascina (PI Italy)

5 University of Florence, Dept. of Information Engineering; Via di S. Marta, 3, 50139 Florence, (Italy) and INFN Sezione di Firenze-Urbino, via G. Sansone, 1, 50019, Sesto Fiorentino (FI) (Italy)

Abstract

Gravitational wave detectors like the Einstein Telescope will be built a few hundred meters under Earth's surface to reduce both direct seismic and Newtonian noise. Underground facilities must be designed to take full advantage of the shielding properties of the rock mass to maximize the detector´s performance. A major issue with the Einstein Telescope design are the corner points, where caverns need to be excavated in stable, low permeability rock to host the sensitive measurement infrastructure. This paper proposes a new topology that moves the top stages of the seismic attenuation chains and Michelson beam re-combination in separate excavations far from

the beam-line and equipment induced noise while the test mass mirrors remain in the main tunnels. Distributing the seismic attenuation chain components over multiple tunnel levels allows the use of arbitrarily long seismic attenuation chains that relegate the seismic noise at frequencies completely outside the low-frequency noise budget, thus keeping the door open for future Newtonian noise suppression methods. Separating the input-output and recombination optics of different detectors into separate caverns drastically improves the observatory detection efficiency and allows staged commissioning. The proposed scheme eliminates structural and instrumentation crowding while the reduced sizes of excavations require fewer support measures.

1. Introduction

Gravitational waves are detected by the relative motion that they induce between isolated test masses separated by large distances. To detect their motion, the test masses are configured as mirrors that form the two Fabry Perot interferometers of a Michelson gravitational wave detector. The test masses need to be extremely well isolated from vibrations that otherwise would overwhelm the gravitational wave-induced motion. All the other optical elements needed to detect that motion are seismically isolated, simply to avoid injecting spurious noise in the test mass measurement. The ubiquitous seismic waves propagating with sub-micron amplitude through Earth's crust cause the so-called seismic noise, which is a mechanical movement that can be filtered away from a gravitational wave detector noise budget using sufficiently long and well-designed seismic attenuation chains (Accadia, et al., 2010). Seismic waves also induce a much subtler effect that cannot be easily shielded, only mitigated by subtraction. They cause tiny fluctuations of rock's density and position, which in turn generate tiny, local fluctuations of

Earth's gravitational acceleration *g*, effectively equivalent to space-time warp. This is called Newtonian noise (Harms, 2019) and its effect on the test masses cannot be distinguished from the effect of passing gravitational waves. If not dealt with it properly, Newtonian noise can impose a limit below 10 Hz to gravitational wave detection. The large density difference between soil and air, the low elastic constant of soil and the larger displacement amplitude - due to both surface waves and body waves that increase their amplitude when surfacing - cause larger Newtonian noise on test masses hanging near the surface. At the surface, air density fluctuations due to infrasound pressure waves and wind turbulence also contribute to Newtonian noise (Creighton, 2008). The air density fluctuations in the atmosphere are not relevant for underground detectors that are sufficiently far from the noise source. Surface waves extend underground with an amplitude that exponentially reduces with depth with a characteristic length that is inversely proportional to the wavelength (Harms, 2019). This means that their contribution to Newtonian noise decays exponentially. Even if the amplitude is diminished by higher rock stiffness, body waves are always present at all depths. Therefore, underground gravitational wave detectors will eventually be limited by the Newtonian noise in the low frequency band. The amplitude spectral density of the seismic displacement decays as $1/f^2$ and the induced Newtonian noise acceleration is proportional to the seismic displacement. Therefore, its amplitude spectral density in the gravitational wave detector strain will fall as $1/f^4$ (Beccaria, et al., 1998). In theory, Newtonian noise could be estimated from a densely spaced network of seismometers and subtracted from the detector signal. This would, however, require many high precision seismometers optimally located around the detector at distances comparable to the seismic wavelength generating the Newtonian noise. The method is limited by the precision and the number of seismic sensors installed and by the mixing of shear and compressional waves that spoils the correlations between the inertial sensors required for the Newtonian noise estimation (Badaracco & Harms, 2019). The quieter conditions inducing less Newtonian noise are the main rationale why future gravitational wave detectors aiming to detect gravitational waves below 10 Hz (Abernathy, et al., 2011) will be built underground. It will be shown that these locations also allow almost optimal deployment of the inertial sensors required for an effective Newtonian noise subtraction.

An alternative approach, chosen for the Cosmic Explorer design (Reitze, et al., 2019), is to make a longer detector on the surface, diluting the fractional error of the larger surface noise with the larger amplitude signal detected over longer distances. Subtraction of the much larger Newtonian noise present at the surface is possible but less effective. At the lowest frequencies needed to detect signals from heavier black holes, underground locations are always advantageous.

Newtonian noise will ultimately impede detection of low-frequency gravitational wave in all terrestrial gravitational wave detectors. Barring new developments, gravitational waves at frequencies close to or less than 1 Hz can only be detected with space probes like LISA (Karsten, D and the LISA study team, 1996) or DECIGO (Kawamura, et al., 2006) or with Lunar gravitational wave antennas like LGWA , GLOC or LSGA (Harms, et al., 2021; Jani & Loeb, 2021; Lognonné, et al., 2021).

It is foreseen that the Einstein Telescope triangle will host three pairs of interferometers (Hild, et al., 2009). Each pair will comprise a room-temperature and a cryogenic detector.

The room-temperature will run with megawatts of standing optical power to reduce the shot noise and increase the sensitivity at high frequency. The cryogenic detector will have kilowatts of optical power, to minimize radiation pressure noise at low frequency. In the noise budget of the present Einstein Telescope Low Frequency (ET-LF) design, the residual seismic noise, suspension thermal noise, Newtonian noise and quantum noise contribute at a comparable level to the low frequency sensitivity limit. Suspension thermal noise can be pushed to lower frequency by longer, more flexible and colder suspensions. Quantum noise can be mitigated by using heavier masses and quantum noise squeezing. Better sensors may be developed to subtract Newtonian noise. These improvements may happen during the 50-year facility lifetime. It is therefore important that the design of the Einstein Telescope facility will not limit the low frequency sensitivity, even for unforeseen future upgrades using techniques that are not yet anticipated. We present a tunneling scheme that can push the seismic noise of the Einstein Telescope Low Frequency interferometer well below the other limiting factors and allow optimal Newtonian noise subtraction. We will also discuss how this scheme will greatly increase the observatory's effectiveness and allow uninterrupted astronomical observations.

2. Structure of present and future detectors

Terrestrial gravitational wave detectors are kilometre-scale Michelson interferometers with arms equipped with Fabry Perot cavities to extend their effective optical length. The Fabry-Perot mirrors are heavy test masses suspended from threads, so that they can be freely accelerated along the beam-line by the space-time fluctuations caused by passing gravitational waves. Present surface detectors (Virgo, LIGO, KAGRA (Aasi, et al., 2015) (Acernese, et al., 2014) (Akutsu, et al., 2018)) have arms 3 to 4 km long, while future detectors currently being designed will be three to ten times longer. In the current surface L-shaped detectors, input test masses, recombination and input-output optics are housed in a single large building. The present design of the Einstein Telescope design has three 10 km long tunnels oriented at 120^{o} from each other, intended to detect both polarizations of gravitational waves. They intersect in three large vertex halls, each containing eight of the twenty-four test masses of its six detectors, as well as the input/output optics of two Michelson interferometers and their ancillary equipment. This configuration has several drawbacks including excessive crowding and mixing the optical components with ancillary equipment such as cryogenic chillers that can cause reverberating acoustic noise, which in turn can inject noise into the input/output optics. Perhaps the worst drawback is that access for maintenance or upgrade on a single detector will affect, and in most cases impede, the operation of all others, thus reducing or interrupting astronomical observations. This drawback is removed by the scheme presented here.

2.1. The ET location

The Einstein Telescope facilities will be at a few hundred meters below the surface. Strong and massive, moderately jointed (i.e. unfractured or slightly fractures) rock mass conditions, dry or with a low hydraulic conductivity are assumed. Underground construction causes a stress redistribution around the excavation that may exceed the rock mass strength or cause rock creep. In tunnel designs with many adjacent excavations redistributed stresses of individual excavations will superimpose and intensify. It is important to avoid small rock pillars between the excavations, such as at the intersection of the large excavations at the corner points, that may fail during the excavation, e.g. due to blast damage or due to superimposed stress states.

The design sketched in Figure 1 is only indicative, the lengths and excavation shapes must be optimized to avoid this kind of structural weakness. The small cross section tunnels proposed here allow more favorable tunnel profiles, i.e. smaller cross section and rounded shapes, while steel arches or reinforced concrete may still be needed in limited places.

Large excavations often suffer from structural controlled instabilities, e.g. rock wedges, that are formed by intersecting discontinuities such as joints or small fault planes, which require heavy rock support, e.g. long (> 6m) and heavy rock bolts or anchors. These stability issues at the target depth of the Einstein Telescope are mostly relevant for the large caverns in the corner points, where the size of the excavation damage zone or structural controlled rock wedges could also be large. The stability of these caverns is improved by reducing the size and by adjusting the shape, i.e. curved side walls instead of vertical side walls, which is made possible by this proposal. Size adjustments can be done in an early design stage by optimizing the distribution of the detector components and their mode of access within the rock mass. Detailed shape adjustments can be considered in a later design stage once the rock mass conditions are known through a site investigation program.

In addition to stability considerations, the corner points host access tunnels or shafts with constraints that need to be considered. Water ingress must be avoided either by an optimal positioning of the facility or by systematic grouting to reduce the rock mass hydraulic conductivity. The ET facility is expected to last 50 years and the LIGO Livingston observatory experience teaches that, in an environment close to 100% in humidity, corrosion can degrade the vacuum works and cause leaks even in pipes built with stainless steel. Underground water and airborne agents are often more aggressive deep underground than at the surface. During the Einstein Telescope operation accumulating or steady-state inflow rates need to be minimized by rock mass grouting and membranes in the lining. All the water must be immediately collected through a drainage pipe system and routed out by gravity if a surface location below the plane of the interferometer is reachable through a sloped borehole or collected in sumps and pumped to the surface. To this regard it is worth considering that the three tunnels should be horizontal at the mid-point, a condition necessary to minimize the projection of vertical thermal noise onto the plane containing the interferometers. In this condition, the three corners are 1.96 m higher than the mid-points and start with a slope of about 0.76 mradian, linearly decreasing to zero at the center. The water therefore naturally flows towards the mid-point. Pumps , where needed, cause an additional source of noise. Thanks to the slope, pumps can be placed far from the corner stations hosting the test masses. Yet, only small flows of water can be disposed with the limited slope available. Therefore, it is a key requirement to position the corner points, and to a slightly lower extent the entire length of tunnels, in massive rock with low permeability. Available data indicates that the Sos Enattos site is likely to satisfy this important requirement. The local mine drainage is of the order of one liter per second for along its ~ 50 km of galleries and the Electrical resistivity tomography of the site shows the absence of significant groundwater, due to the low porosity of the rock (Naticchioni, et al., 2020).

2.2. The proposed tunnel scheme

The tunnel scheme, sketched in figure 1, takes best advantage from the underground environment for building gravitational wave observatories. It consists in several small and therefore more stable interconnected excavations[a]. Angled beam-reducing telescopes positioned upstream of the Input Test Masses produce extracted beams that propagate at a 15^{o} angle away from the Fabry Perot beams, so that the recombination on the beam splitter happens at the optimal 90^{o}. Positioning the Input Test Mass and their beam-reducing telescopes at a suitable

[a] Many of the solutions presented in this paper are like those the author invented and/or designed for the KAGRA detector that is the first built underground. Many of the illustrations are borrowed directly from that design. Only cursory description and suitable references are provided wherever suitable information is available elsewhere. Detailed design aspects are presented as online-only additional material.

distance along the main tunnel directs the extracted beams of the two Michelson interferometers to separate excavations housing the beam-splitter and input/output optics (DeSalvo, et al., 2022). The fundamental limitations of low-frequency sensitivity of gravitational waves, quantum noise, radiation pressure, and suspension thermal noise are not addressed here but we note that mitigation of suspension thermal noise requires cryogenics as well as substantial vertical space above the test masses, which are easily made available by this scheme. The scheme is also suitable for upgrades to heavier masses to reduce the quantum back-action noise.

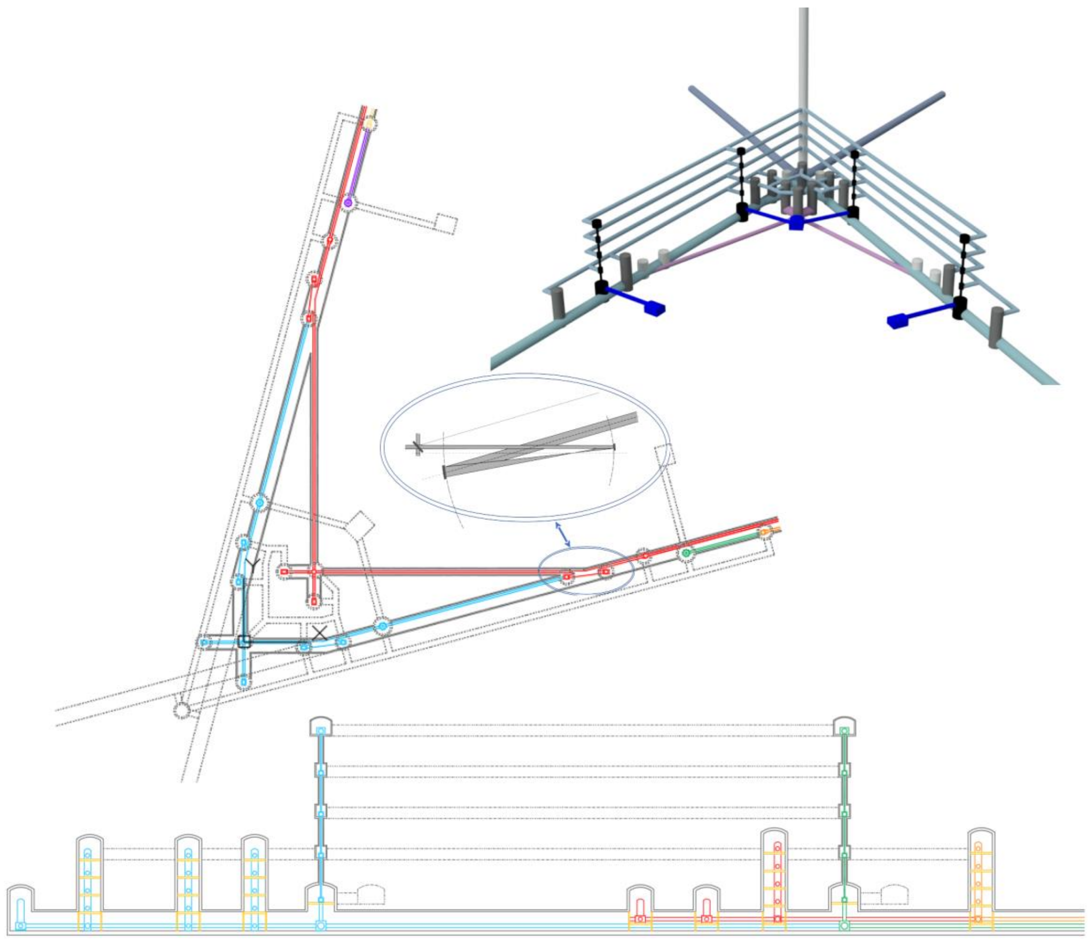

Figure 1: Top: Scheme for separate extraction of multiple interferometers from the main tunnel and possible structure of access tunnels. An insert zooms on the beam-reducing telescopes that extract the Michelson beams from the main tunnel. The room temperature interferometer, which is located above, (red) is extracted first, thus leaving more space for the cryostat of the low frequency detector (blue). Input and output optics (not detailed here) are housed together with the

beam splitter in separate L-shaped excavations. Bottom: Elevation view of possible vertical structures satisfying the different kinds of seismic attenuation chains. All access tunnels (behind or in front of the tunnel section) are represented in both panels with dotted lines. The 3D insert is a sketch provided to guide the eye, an interactive version is provided in the online-only section.

The two taller structures in the lower panel of figure 1 are stacks of alcove excavations connected by a vertical borehole, each harboring one of the vertical attenuation filters separated by pendulums longer than 10 m. They provide isolation for the most demanding cryogenic test masses of the low frequency interferometers. The dotted alcoves near the base of these stack house the cryogenic chillers. Any other noisy equipment can be housed in similar alcoves. The five intermediate-length towers are for other main optical elements, they may be of different kinds and heights, depending on specific requirements. The three smallest structures contain seismic isolation for optical benches and other less demanding optics. Note that the top stages eliminate space encroachment at the beam-line level. The inverted pendulum and top filter at the head of the chains sit directly on the rock in the top alcove. Alcoves with narrow and sealable access tunnels proved very effective to isolate from ambient noise or vibrations induced by ventilation or other machinery. When installing seismometers in the Homestake mine (Harms, et al., 2010) it was observed that the instruments installed in similar alcoves had the lowest noise floor.

All structural encroachment around the Test Masses is eliminated by supporting the seismic attenuation chains from above, which is especially valuable in the locations where the beams of the high frequency interferometer peel off from the main tunnel and to make space for the cryostats. The Test Masses can be simply housed at the ends of the 10 km tunnels with little or likely no local tunnel enlargement. Cryogenics and other noisy machinery can be isolated in nearby separate caverns shielded by meters of rock, connected by relatively short heat links running through horizontal drilling but remaining continuously accessible for maintenance.

Other advantages provided by the proposed scheme are detailed in the following sections.

We stress that the sketch of figure 1 is only conceptual, reasonable dimensions are suggested but not optimized. The two extreme solutions outlined for seismic attenuation can be scaled to meet the different requirements of various optical elements while maintaining easy access to all attenuation chain elements. Exact topology, height, load or size of attenuation stages for different optical elements are not determined. Similarly, no effort is made here to decide excavation shapes and sizes, or to decide spacing along the beams to eliminate interference between different detectors. This will be object of a tradeoff study involving mining engineers and physicists, with the aim to minimize costs while maintaining safety and satisfying the scientific requirements. A rough cost comparison between the ET baseline design and the one proposed here was made (Wannenmacher, 2021). The larger excavation volume of one balance the greater complexity of the other. Within the error margin of both still largely tentative designs, they found no significant cost difference.

2.3. Present Seismic Attenuation Systems

Seismic noise attenuation comes from the natural properties of a pendulum, which attenuates horizontal vibration transmission with a $1/(f^2 - f_0^2)$ function that provides a cutoff starting above the pendulum resonant frequency $f_0 = \sqrt{g/l}/(2\pi)$ where l is the pendulum length and g is the gravitational acceleration. The mechanical attenuation is provided by a chain of pendulum wires alternated to massive vertical attenuation filters (discussed in Section 3.3) acting as pendulum mass. Each stage contributes a $1/(f^2 - f_0^2)$ attenuation starting from its corresponding resonant frequency. With *n* stages a $1/(f^2 - f_0^2)^n$ attenuation power is achieved

(Saulson, 1994). Therefore, seismic attenuation performance on the low frequency side is limited by the length of the pendulums used, which are limited by the available height above the Test Masses.

The overall length of the seismic attenuation chains of present detectors ranges from a couple of meters in LIGO (Aasi, et al., 2015), to seven meters, in Virgo (Acernese, et al., 2014). Most present detectors (except for KAGRA) rely on support structures extending up from the beam line floor, whose base encroaches in the space around the test masses. Tall structures need to be very stiff to avoid amplifying ground motion and their height is limited by the hall that hosts them. Individual pendulums in present detectors are limited to lengths of the order of a meter, with resonant frequencies (start of passive attenuation) around 0.5 Hz, which are adequate for a detection threshold above 10 Hz but would require a large complement of active attenuation to reach lower detection frequency.

2.4. Einstein Telescope Seismic Attenuation System and longer chains

Einstein Telescope aims to be sensitive below 10 Hz, thus requiring the start of the $1/(f^2 - f_0^2)$ roll offs at lower frequencies than present detectors, and therefore longer pendulums. The attenuation chain length in the present Einstein Telescope design is limited by the excavation ceiling height housing 17 m tall towers (Abernathy, et al., 2011), containing six stages of pendulums, each with less than 3 m long suspension wires. The pendulum resonant frequencies of 3 m long pendula are close to 0.3 Hz (0.49 Hz in Virgo 1 m pendula). With these limitations in vertical size, seismic noise remains a small but non-negligible source of disturbance at the lowest frequencies, which may become a limiting factor if new ways are found to further depress quantum, suspension thermal and Newtonian noise. In addition, there are serious concerns about the interferometer controls. Forces are needed to lock the interferometer and to compensate for the residual motion of the suspension chains below the gravitational wave detection band. These forces are suspected to generate up-conversion of low frequency noise or otherwise contribute control noise in the detection band (Buikema, et al., 2020). There is an advantage in lowering the isolation system resonant frequencies because the required control forces are reduced. This is particularly important if the effect of the micro-seismic peak can also be mitigated.

2.5. Sensing Low Frequency Seismic noise

Regarding the reduction of the micro-seismic peak and other low-frequency seismic noise, it should be noted that after acquisition of Fabry-Perot lock each pair of Test Masses effectively form a single, rigid inertial mass hanging from two widely separated points subjected to the seismic noise of two vertices of the triangle. After the Michelson lock acquisition, the four Test Masses of each interferometer form an even larger inertial mass with suspension points extending to all three vertices. Optical levers, augmented with fringe counting, provide length sensing between each test mass and the surrounding rock. In the Einstein Telescope triangular topology, the six detectors provide six independent measurements of the low frequency seism with two different suspension frequency tunings and three orientations. These redundant signals can be combined to form synthetic seismometers measuring the low frequency seism at all three vertices with noise floor far below that of commercial sensors. Their signals can be used to suppress the effects of low frequency micro-seismic noise on all Inverted Pendulums.

3. Advantages of the proposed Configuration

3.1. Segregating different detectors in separate caverns.

Decoupling the maintenance, upgrades and/or commissioning of different detectors in the Einstein Telescope is of capital importance because, if work can be done on one detector without affecting the operation of the others, continuous observation mode can be maintained.

The way to relegate the recombination and input-output optics of different detectors in excavations separated by tens of meters of rock is discussed in (DeSalvo, et al., 2022). The key point is that a few meters of rock provide much more isolation than that existing between the interferometers and their control rooms in present surface detectors. Therefore, working on a detector in most cases can be expected to not affect the operation of the other five. Similarly, access in the main tunnels housing the Test Masses may not affect the operations because the support points of the seismic attenuation chains reside at higher tunnel levels and therefore insensitive to tunnel access.

3.2. Advantages of multiple tunnel layers for lower-frequency seismic noise suppression

The proposed topology provides effectively unlimited vertical space and pendulum lengths. The start of the $1/f^2$ roll off at lower frequency shifts the seismic noise farther from the Einstein Telescope detection frequency band and reduces the required control forces. Consider, for example, filters housed in 4 m tall excavations vertically separated by 8 m of rock. The resulting ~ 12 m separation between filters is four times the present Einstein Telescope design, producing <0.15 Hz pendulum resonances[b]. This arrangement, assuming the same number of filters, would push the seismic attenuation wall at half the frequency of the current 17 m design. This of course is true only if the better performance of longer pendulum lengths can be matched

[b] Chaining multiple pendula produces a characteristic spread of resonances around this center value. The point is that longer wires shift the distribution down in frequency as $1/\sqrt{l}$.

by vertical attenuation filters [c] (Cella, et al., 2002; Cella, et al., 2005) tuned to resonances at or below 0.15Hz.

The attenuation performance of a 60 m long chain is compared (without changing the mirror suspension design) in figure 2 with that of the 17 m chain of the Einstein Telescope baseline design. The expected start of the attenuation curve at half the frequency is visible in the simulation at ~ 0.55 Hz. The structure above 0.55 Hz is contributed by the not yet optimized final suspensions that limits the gain for frequency above 1 Hz. The displacement noise is compared in figure 3 by folding the attenuation transfer function of figure 2 with a typical underground seismic spectral noise (Data from ref. (ORFEUS, 2022)). Additional simulations show that with longer suspensions, made possible by the proposed topology, the full gain from the longer wires can be recovered.

3.3. Advantages of separating the top of the seismic isolation chain from the Test Mass level

The scheme for seismic attenuation illustrated in figure 1 envisions vertical stacking of small excavations connected with boreholes for the pendulum wires. The only connections to ground are through the pre-isolators, which are relegated to the top level, and the cryogenic heat links (Chen, et al., 2014) that can be positioned at a suitable intermediate level. The noisy cryogenics chillers can be housed in separate halls with heat links running through boreholes, with anchoring to rock designed to shield out compressor vibrations. A similar topology for the

[c] The horizontal planes of test masses located 10 km apart differ by ±0.8 mradian due to Earth's sphericity, which feeds part of the vertical seismic noise into the horizontal detector plane. In addition, mechanical asymmetries due to control systems and machining errors contribute to inject vertical noise in the horizontal direction at a fraction of percent level at all stages. Therefore, the vertical seismic noise must be attenuated simultaneously, stage-by-stage together with the horizontal one.

KAGRA cryostat (Akutsu, et al., 2018) was designed even if the extra vertical space was not needed there.

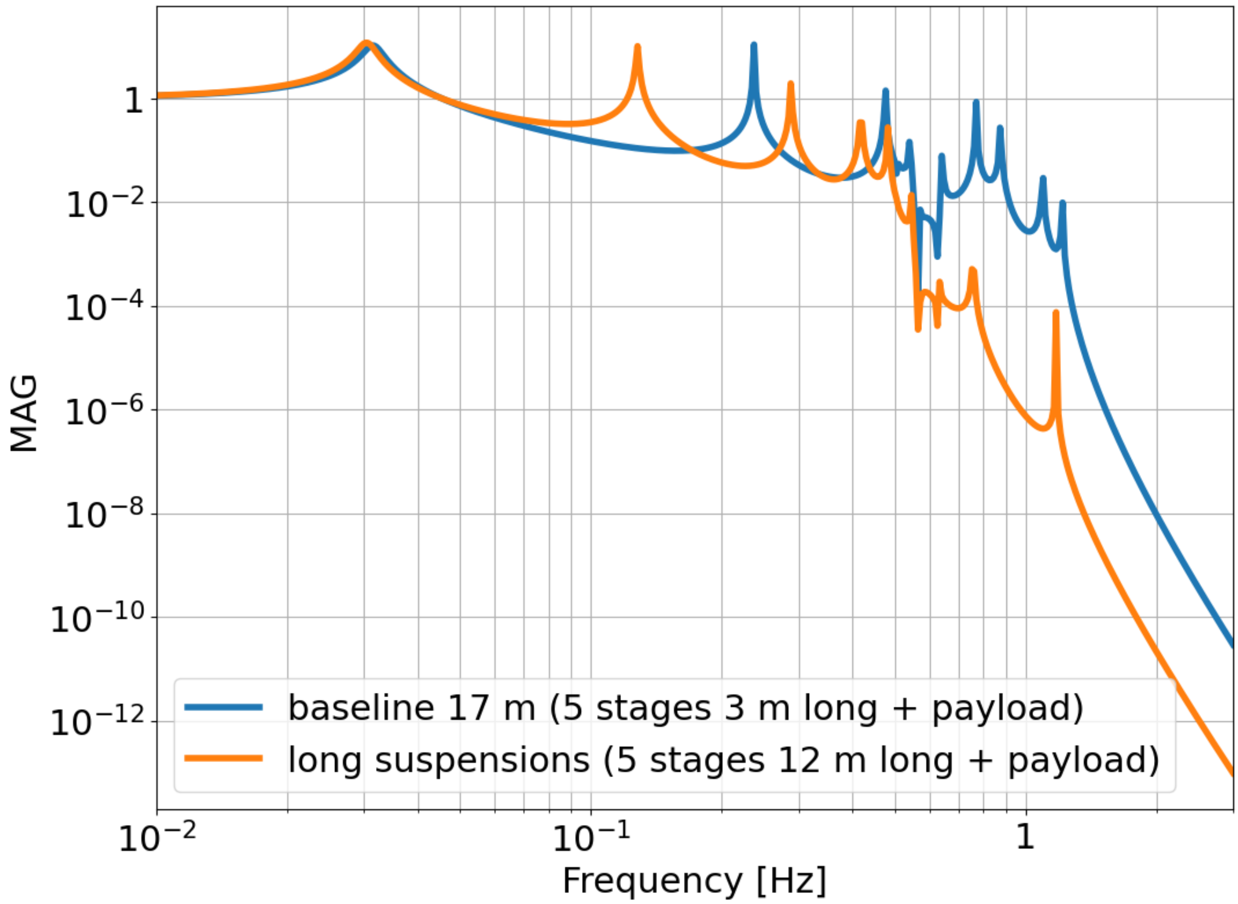

Figure 2: Comparison between the Einstein Telescope baseline seismic attenuation scheme with 3 m separation between filters and the same configuration with longer separation between filters. The mirror suspensions are the same in the two simulations, without re-optimization for lower frequency performance.

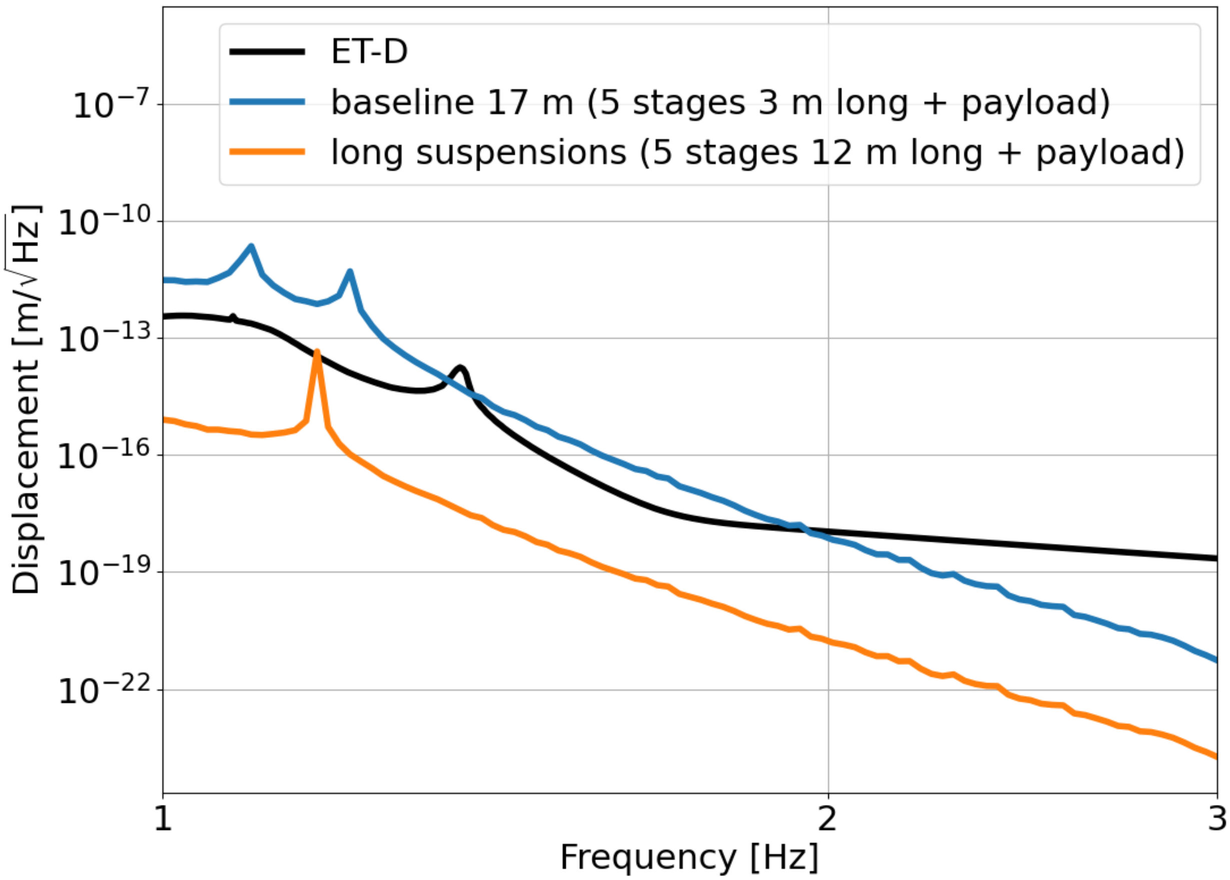

Figure 3: Comparison of the expected displacement noise after convoluting the transfer function with a measured seismic noise. The optical length sensing is expected to have a sensitivity around 10^{-18}m/√Hz in this frequency range.

3.4. Smaller vacuum chambers for the test masses

Virgo and LIGO have large vacuum chambers requiring human access for installation and maintenance, which causes persistent cleanliness problems. Side access has been successfully used in Japan since the TAMA detector. Relocating the seismic attenuation and cryogenics away from the beamline level allows installation of even large optics in much smaller vacuum chambers. Much cleaner working conditions can be obtained if the operator does not need to enter the vacuum chamber and can work through the side, from an ergonomically placed platform while the optics are continuously protected by a flow of clean air provided from above.

The scheme illustrated in figure 4 was designed for the mid-size mirrors used in KAGRA for beam size reducing telescopes (recycled initial LIGO test masses) but can be adapted for larger and cryogenic optics as well.

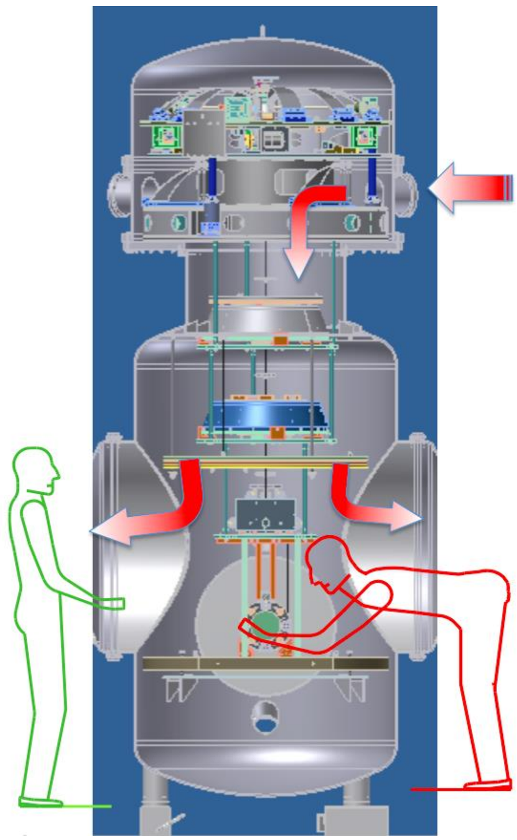

Figure 4: Ergonomic access scheme to large optics in a reduced-size, side-access vacuum tank. The operators remain outside the vacuum chamber, thus reducing chances of introducing pollutants. The red arrows indicate a clean air flow. Having removed the encumbrances from the seismic attenuation structure, the same scheme can be applied to large size optics, including cryostats equipped with removable lateral thermal shield panels, similar to those implemented in KAGRA.

3.5. Access to suspension elements of the cold and warm interferometers

In the wide excavations proposed for the Einstein Telescope, tall and complex support structures surrounding the test masses and extending along the full chain's height are needed to support the top stage of the seismic attenuation chain and to access the filters for tuning and maintenance. These structures pose significant technical challenges and risks. An example of a support structure designed to minimize seismic noise amplification of the top stage of the seismic attenuation chain is shown in figure 7 of the online-only section.

Side-access vacuum chambers footed in the alcoves, or rock-anchored platforms in the shorter-chain wells provide safe access to each element of the seismic attenuation chain for installation, tuning and even upgrades like implementation of heavier mirrors.

4. High Frequency Einstein Telescope detectors

The Einstein Telescope High Frequency detectors (Hild, et al., 2009) feature less demanding requiring attenuation chains with much shorter pendulums. The stacked alcove scheme becomes unnecessary. These attenuation chain components can reside in cylindrical vacuum chambers, with side access for maintenance and tuning. They would be housed in rise-bore shafts extending above the main beam tunnel. The attenuation tower would be offset from the center of the well, with balconies attached to the side walls for ergonomic access to the chain elements. Their pre-isolator would reside on short beams anchored to the rock. The number and size of filters needed would depend on the requirement of each specific optical element.

5. More on seismic attenuation

5.1. Vertical attenuation filters

Because of unavoidable mechanical imperfections and the effects of Earth's sphericity vertical and horizontal mechanical noise mix along an attenuation chain (Accadia, et al., 2010). Attenuation performance in the horizontal plane is futile if not accompanied, at every stage, by matching vertical attenuation. Suitable vertical attenuation can be achieved using modular Geometric Anti Spring filters in appropriate number and size to match the requirement of each individual optical element. The Geometric Anti Spring filter is a mature technology used in Virgo, HAM-SAS (Sannibale, et al., 2008), TAMA (Marka, et al., 2002), KAGRA and scientific and commercial platforms. They are sophisticated but simple mechanical oscillators that can be tuned to low resonances. Examples of two kinds of filters that can be re-sized to satisfy all the Einstein Telescope requirements are illustrated in figure 5. The low frequency operation (0.12 Hz) was achieved for the top Geometric Anti Spring filters of KAGRA, illustrated in figure 6. This already matches the resonant frequency of the longest pendula envisaged here.

Anti-spring pre-tuning at ~300 mHz is easy but it becomes critical below 200 mHz. In situ resonant frequency tuning is allowed by the side access in the alcoves. Tuning of the vertical working point is critical, as evident in figure 6, and becomes increasingly difficult as the resonant frequency is tuned to lower values because the frequency vs. height curve becomes narrower, thus requiring a match of the spring strength to the payload weight at $<10^{-4}$ level. That can be achieved with thermal control of individual filters, taking advantage of the $\sim 3\ 10^{-4}$/K change of steel's Young modulus with temperature. A range of up to 100 K of heating is allowable without inducing creep on properly treated maraging springs (Virdone, et al., 2008) while a range of only several degrees is needed. A precision of a tenth of a degree, easily achievable in a vacuum tank, is adequate to maintain the required load matching.

5.2. Pre-isolator

A pre-isolation filter is foreseen at the top of each optical chain. It is composed by a short inverted-pendulum supporting a large-size Geometric Anti Spring filter. Short inverted-pendulums have the same attenuation power of longer ones without being affected by the low-frequency internal resonances of longer legs. By sitting directly on hard rock, the pre-isolators don't suffer from the amplification of ground tilt affecting tall structures (Tshilumba, et al., 2014; Accadia, et al., 2011), this is an invaluable advantage. The simple coupling of an inverted pendulum and a Geometric Anti Spring filter (Stochino, et al., 2009; Losurdo, et al., 1999) provides a passive attenuation power equivalent to that of the entire Advanced LIGO active isolation without its control complexity (Hua, et al., 2004). While fundamentally a passive element, the pre-isolator is also an ideal platform for active reduction of low frequency seismic noise with inertial sensor signals (Wanner, et al., 2012; Dahl, et al., 2012) or to apply feed-forward from other signals (Kirchhoff, et al., 2020; Marvin & Lantz, 2013).

5.3. Shorter chains

Seismic isolation for less demanding and auxiliary optics can be satisfied with compact chains like those used for the main mirrors in KAGRA, as illustrated in figure 7 online. The mechanical structures designed to mitigate the amplification of ground tilt on raised structures (figure 8 online) are complex. Even for short chains, this complexity and space encumbrance can be avoided by attaching the top stage of the seismic attenuation chain to the rock above.

5.4. Test Mass suspensions

The test masses in present, and likely in future room temperature detectors, are suspended using fibers made of fused Silica (Cumming, et al., 2021). Silicon, Sapphire, or other crystal rods will be needed to suspend and cool test masses in low-frequency cryogenic detectors (Amico, et al., 2004; Khalaidovski, et al., 2014). In the Einstein Telescope the suspensions will need to be longer and softer than in present detectors to reduce the suspension thermal noise that dominates at low frequency; yet they must have sufficient thermal conductivity to keep the mirrors at cryogenic temperatures. The design of the mirror suspension solutions with large compliance and thermal conductivity are not considered in this paper but this scheme removes any limitation of vertical height for mirror suspensions.

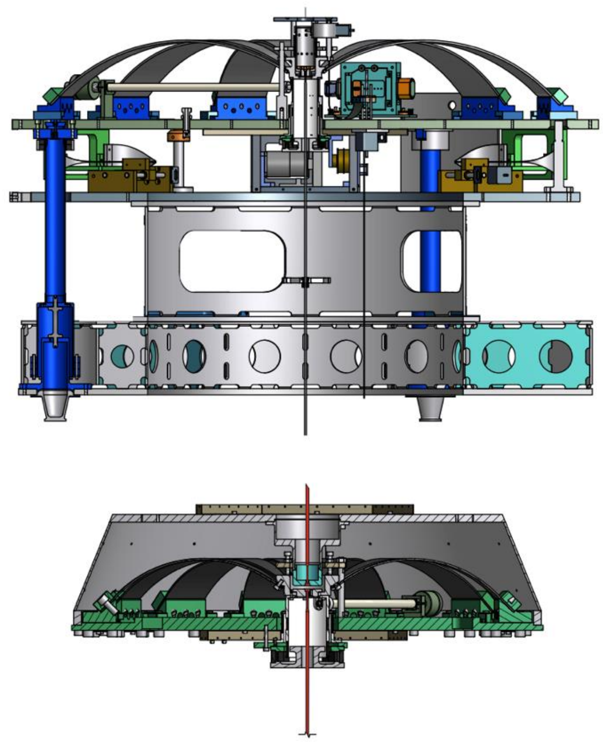

Figure 5: A pre-isolator (top) and of a standard filter (bottom) designed and built for KAGRA. The pre-isolator is composed by a short inverted pendulum footed directly on the bedrock in a cavern above. It supports a large Geometric Anti Spring filter that in its turn suspends a chain of standard filters. Both can be scaled to the heavier payloads of the Einstein Telescope.

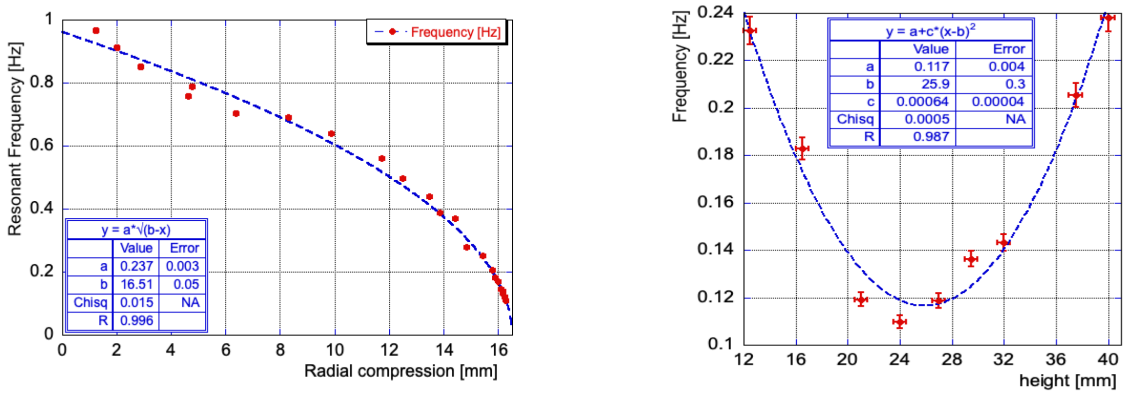

Figure 6: Tuning of a KAGRA pre-isolator Geometric Anti Spring filter. Left: Frequency tuning of the resonant frequency obtained by radial compression of the cantilever blades forming the Geometric Anti Spring mechanism **(DeSalvo, 2007)**. Right: Dependence of the resonant frequency from the working point; the different points in the plot are obtained by adding or removing ~100 g masses to the ~ 1 ton payload. In situ the working point can be fine-tuned via controls of the temperature of the vacuum tank.

6. Flexibility advantage and possible limitations

The argument for large halls in the present Einstein Telescope design was to provide more flexibility for future improvements of the facility, but the drawback is that working on a detector will impede operations with all other detectors in the same cavern and thus stop all astronomic observations. The physical separation of recombination optics of different detectors into individual and properly sized halls, the support of the isolation chain of all test masses in alcoves also separated by many meters of rock and the relegation of noisy equipment in separate and sealed excavations will allow to work on a detector while the others remain in astronomical observation mode. Having vertically separated seismic attenuation support points from the optics level allows for a much lower ceiling in the halls.

If unforeseen improvements of the other noise sources were somehow developed, seismic attenuation can be pushed to even lower frequencies by excavating new alcoves above the initial ones.

It may be argued that the positioning of the seismic attenuation chains in wells may impede length tuning or reconfiguration of the optical cavities. Actually, only the Fabry Perot lengths are difficult to change, but there is no conceivable reason to do it for tuning purposes. All input/output optics are in the recombination halls and can be reconfigured as needed within the constraints of the wells housing the tallest attenuation chains and at will for the shorter chains. If the reconfiguration required is drastic, even relocation of tall chains can be done using standard refilling and re-boring techniques. This would clearly be a not negligible change, but comparatively low-impact and feasible during major upgrades of individual detectors.

7. Drilling radial boreholes for Newtonian noise subtraction sensors

Effective Newtonian noise subtraction techniques require finely-spaced high-sensitivity sensors in the rock mass surrounding the test masses. These sensors must be distributed in a radially layered pattern. This is a large and expensive endeavor that may be justified only after the detector has reached sufficient low-frequency sensitivity. Experience shows that it takes years of development for the detector to reach this stage. It is thus necessary that the Newtonian noise mitigation can be staged and/or implemented at a later time.

The required instrument pattern can be achieved with maximized effectiveness and minimized costs by directional drilling of a set of radiating boreholes originating from tunnels located near the three recombination point locations. Drilling from a tunnel eliminates the wasted length of boreholes starting from the surface. Modern directional boring techniques developed for oil extraction and ore exploration[d] (Milazzo, 2022) allow a more efficient and easily expandable boring geometry. Implementation of custom triaxial inertial sensors with remote anchoring/release and alignment mechanisms along each borehole will minimize drilling length. Boreholes can be extended as needed after removing existing sensors. Rock strain sensors can also be installed along the boreholes. Standard diameter boreholes, i.e. 130-170mm, are adequate to house custom instruments can be of hundreds of meters in length. The requirements in space and power for the drill rig mainly depend on the borehole length and diameter. The tunnels hosting the required drill rig for the radial drilling would be positioned at a sufficient distance from the detectors that the boring vibrations would not cause lock loss and only marginally affect the observatory sensitivity and operations. Boring produces mostly high frequency vibrations: several tens of meter of hard rock separation between the boring point and the support points of the attenuation chains, together with the natural $1/r$ amplitude attenuation of radiating perturbation, reduce the effects of the vibrations caused by the boring to the point that passing through the seismic attenuation chain channel can affect the test masses.

Vibration may still affect the length sensing of the interferometers through other channels like scattered light and possible up-conversions in control signals, and even Newtonian noise. The radiated vibration can be monitored with nearby geophones. Therefore, if drilling is performed during observatory operation, it can be regarded as a "known" point-like source of noise. If any sensitivity degradation is observed during drilling operations, modern signal

[d] Drill 6-8-10 inch diameter change price per meter by 15-20% per step, and require 400 HP drill motor. Using 3 m rod elements can work within a 6-8 m diameter tunnel. A record they achieved was horizontal drilling for over 400 m long starting from a tunnel at 700 m depth.

correlation techniques may identify, quantify, and possibly localize channels of length sensing noise injection. It may even become an effective diagnostic tool to identify and possibly eliminate, or exclude, what otherwise may remain as a poorly understood noise intrusion channels that limit the sensitivity.

8. Conclusions

It has been shown that future underground gravitational wave observatories like Einstein Telescope can perform better if built with longer attenuation chains housed in multiple small, interconnected excavations rather than the large halls foreseen in the present design of the Einstein Telescope.

The first and foremost gain is the improvement of the observatory astronomical observation efficiency that is obtained by physical separation of the six detectors. Perturbations caused by work on a detector do not affect the operation of the other five. This allows staged installation, maintenance or upgrades of a detector while maintaining all other ones in observation mode. Gaps in gravitational wave observations and the risk of missing a rare, and potentially multiple-messenger, close-by event like a supernova or a neutron star merger are eliminated.

Small size excavations allow to separate noisy equipment, like cryogenic refrigerators and vacuum and water pumps, from the optics and shield them by meters of rock to reduce vibration re-injection.

The second advantage is that arbitrarily long attenuation chains with lower frequency performance can be built by making use of the rock environment. As a result, seismic noise can be pushed far from the detector noise budget and keep the door open for future sensitivity improvements. Lower frequency attenuation also reduces the chance that up-conversion of control noise may end up limiting the detection sensitivity.

The cost of boring and of high-quality inertial sensing instruments is relevant, and the quality of sensors continuously improves, therefore full-fledged Newtonian noise suppression may not be fully implemented initially. The proposed tunnel topology is suitable for implementing and staging instrumentation for Newtonian noise subtraction without interrupting astronomical observations.

Depending on the outcome of geological site investigations programs, the design needs to be adjusted to account for the anticipated rock mass conditions.

The concepts presented here are thought for the present triangular Einstein Telescope design, but some also apply to underground “L” geometries.

Acknowledgments

RDS likes to remember the many discussions with his late father Francesco, mining engineer and mine director, he contributed many of the ideas presented in this paper.

The figures representing examples of seismic attenuation components were originally provided by RDS for KAGRA.

We would like to thank Alessandro Bertolini, Aniello Grado, Francesco Fidecaro, Giacomo Oggiano, Luca Naticchioni, Joris van Heijningenfor useful criticism and discussions and Gianni Gennaro for the KAGRA graphics.

Online Only

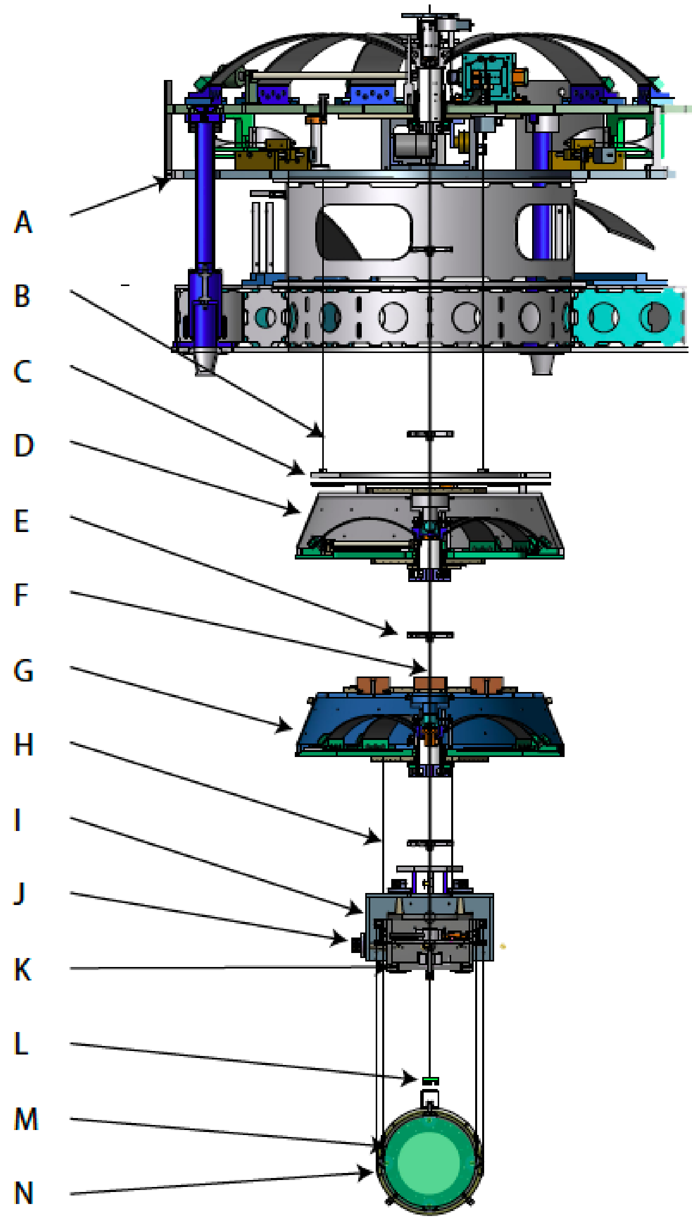

Figure 7: Example of a typical seismic attenuation chain; length of wires, size and number of filters would depend on the mass and requirements of the optical payload. A: Pre-Isolator, B: Magnetic damper wires, C: Magnetic damper disk, D: Standard filter, E: cabling spider, F: Suspension wire, G: Bottom filter, H: suspension wires of intermediate mass control box, I: intermediate mass control box, J: OSEM position sensor/actuator, K: Intermediate mass, L: whip magnetic damper of mirror recoil mass, M: mirror, N: mirror recoil mass.

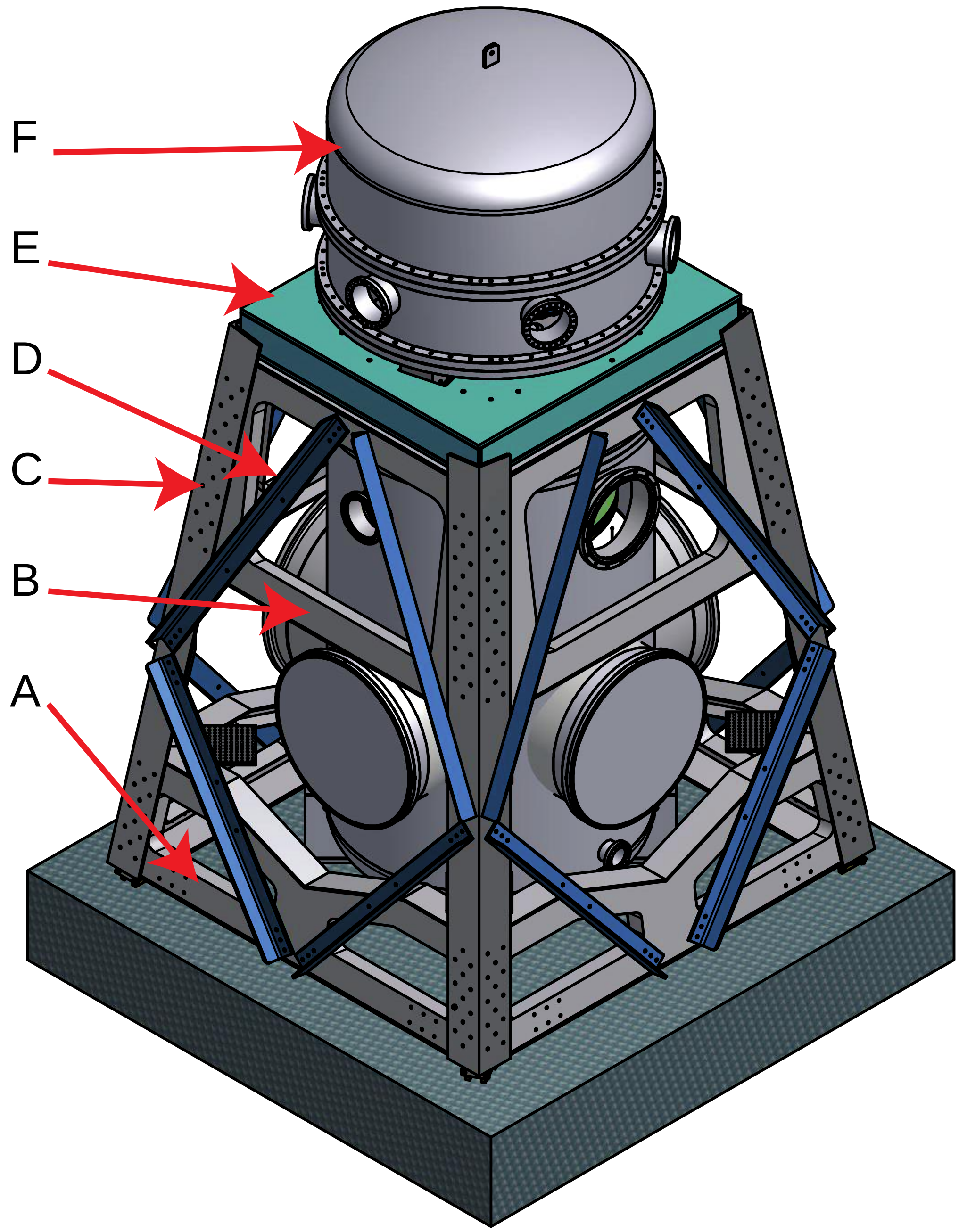

Figure 8: Illustration of an external support structure supporting the seismic attenuation head of a compact Seismic attenuation chain. Bolted structures are always found to have resonances different and lower in frequency by as much as a factor of 2 than in simulations. This is because in simulations connections between parts are rigid, as welded, while in bolted structures the connections are always the weakest point. To mitigate this, this support structure is built by two welded frames (A and B) connected by four over-bolted heavy L-beams (C). Over-bolting was common in building bridges before welding was introduced and is important to increase resonant frequencies. Lighter, angled, bolted L-beams (D) sandwiching a dissipative rubber layer both stiffen and damp these resonances. The top platform (E) supports, through

bellows, a short, inverted pendulum pre-attenuator like that of figure 5 housed in a removable dome (F). A much larger and more complex structure would be necessary for the Test Masses to avoid amplifying low frequency seismic tilt noise. Such structures would heavily encumber the space around the test masses.

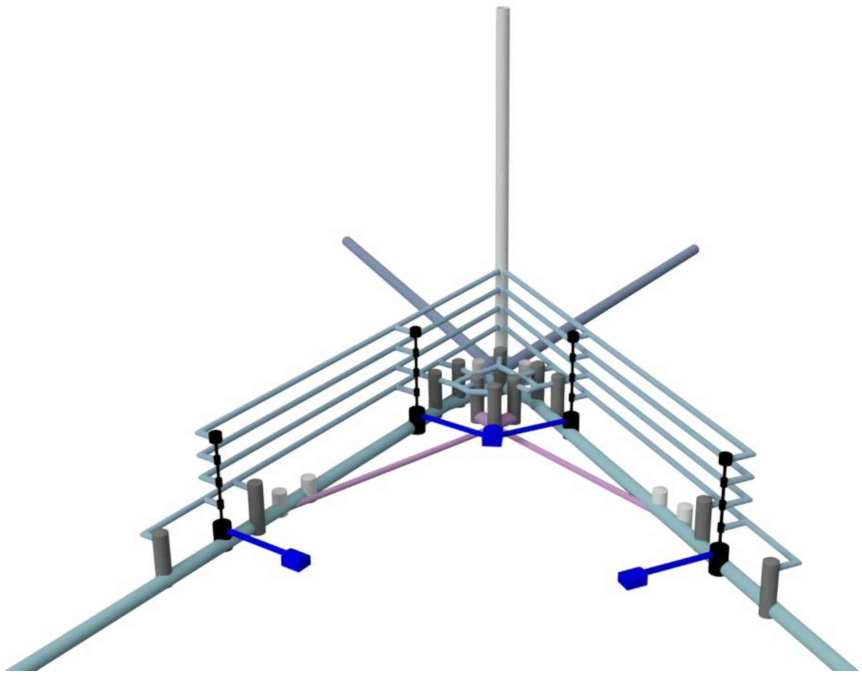

Figure 9: Interactive illustration of a possible tunnel configuration with access to the different alcoves and raise bore wells housing the components of the gravitational wave detectors **(the interactive file can be downloaded from [here](#) and rendered using this [viewer](#))**. All noisy components, like the cryogenic chillers, are housed in separate alcoves to confine their noise. The tall vertical well, may extend to the surface providing a required secondary escape route. Note, the main tunnels are illustrated as extending beyond the crossing point. A horizontal tunnel may house the required mode cleaner and vacuum squeezing cavity. The second, angling up, may be the TBM arrival route. If it was convenient to assemble the TBM at the surface the tunnel would provide the main access route.

Figure 10: Typical raise bore head (reamer), which rotates and is pulled by drill rods through a smaller borehole that was drilled prior to the widening process. It is used to widen up vertical boreholes; the muck falls in the tunnel below and is periodically mucked out. Several options are available to build small-diameter shafts: raise drill https://www.herrenknecht.com/de/produkte/productdetail/raise-boring-rig-rbr/ or boxhole boring https://www.herrenknecht.com/de/produkte/productdetail/boxhole-boring-machine-bbm/

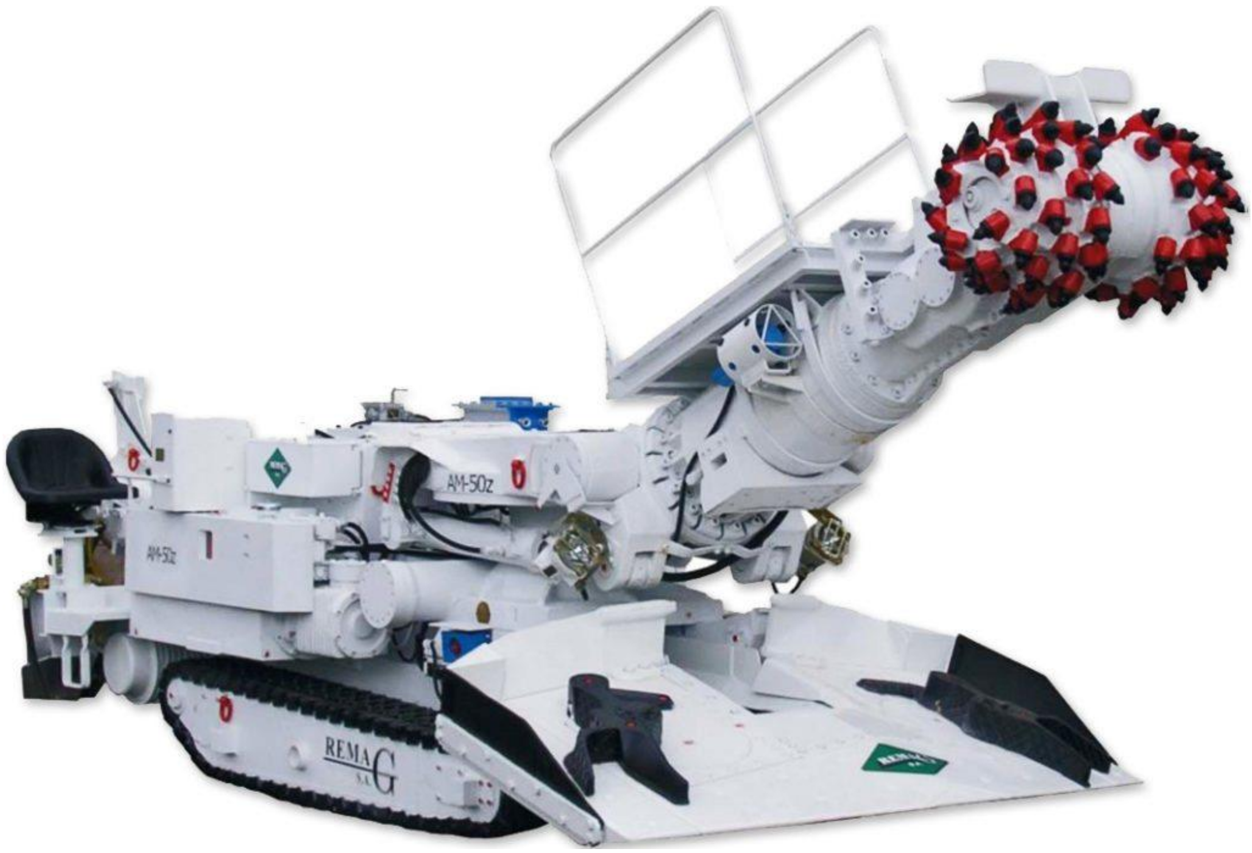

Figure 11: Typical roadheader (https://alpinecutter.com/en/products/roadheaders/new-roadheaders.html) While drill and blast is likely more convenient to dig the alcoves and their access tunnels, a roadheader may be needed to descale and smooth out the walls and ceilings, but especially the floors of the alcoves where the heads of seismic attenuation chains need to be solidly attached to solid rock.

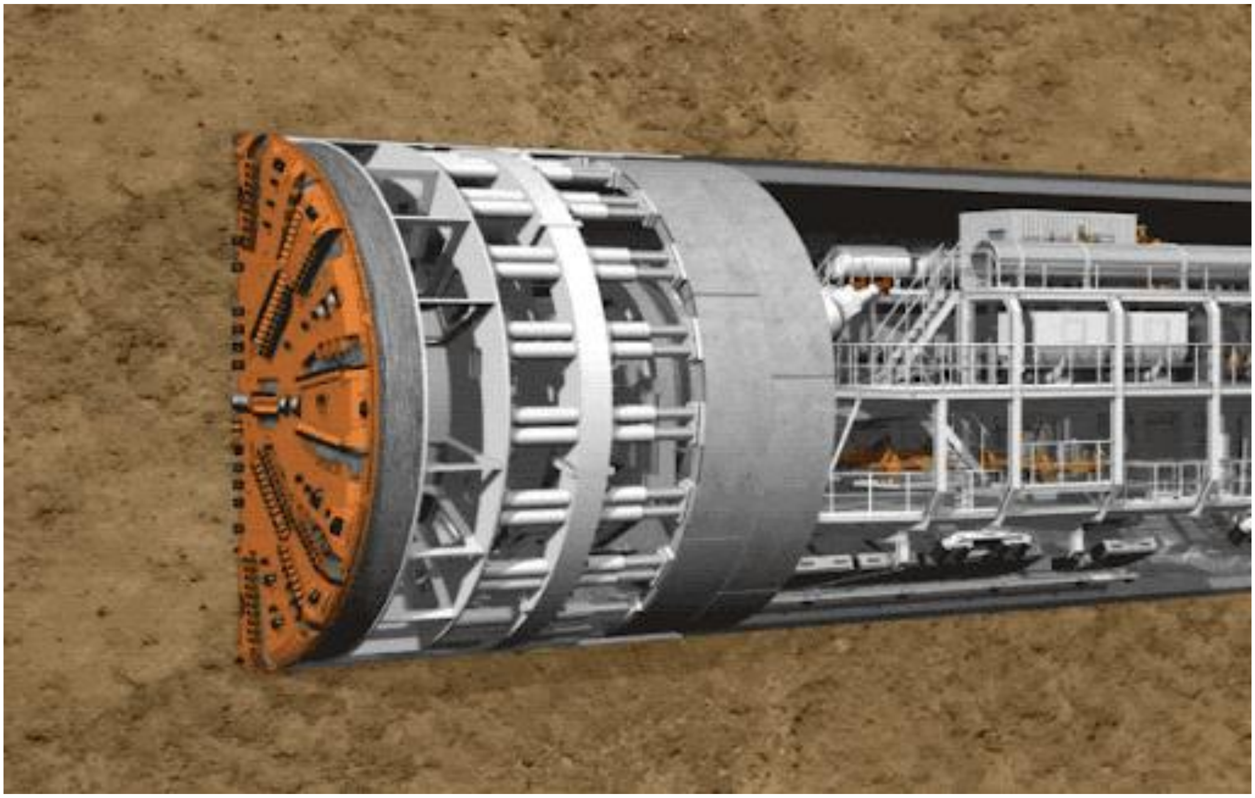

Figure 12: Operation of a Tunnel Boring Machine, used to cut long tunnels (http://www.cat-bus.com/2018/01/far-from-boringmeet-the-most-interesting-tunnel-boring-machines/) Solid and mostly unfractured rock is a requirement for the ET tunnels. The lining would not be necessary, except in places where fractures would be found.

References

Aasi, J. et al., 2015. Advanced ligo. *Classical and quantum gravity,* 32(7), p. 074001.

Abernathy, M. et al., 2011. Einstein gravitational wave Telescope conceptual designstudy. *ET-0106C-10.*

Accadia, T. et al., 2010. The seismic Superattenuators of the Virgogravitational waves interferometer. *Journal of low frequency noise, vibration and active control,* p. 63 – 79.

Accadia, T. et al., 2011. A state observer for the Virgo inverted pendulum. *Review of scientific instruments,* 82(9), p. 094502.

Acernese, F. et al., 2014. Advanced Virgo: a second-generation interferometric gravitational wave detector. *Classical and Quantum Gravity,* 32(2), p. 024001.

Akutsu, T. et al., 2018. Construction of KAGRA: an underground gravitational-wave observatory. *Progress of Theoretical and Experimental Physics,* 2018(1), p. 01.

Amico, P. et al., 2004. Thermal noise reduction for present and future gravitational wave detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 518 (1-2), pp. 240-243.

Badaracco, F. & Harms, J., 2019. Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves. *Classical and Quantum Gravity,* 36(14), p. 145006.

Beccaria, M. et al., 1998. Relevance of Newtonian seismic noise for the VIRGO interferometer sensitivity. *Classical and Quantum Gravity,* 15(11), p. 3339.

Buikema, A. et al., 2020. Sensitivity and performance of the Advanced LIGO detectors in the third observing run. *Physical Review D,* Volume 102, p. 062003 .
Cella, G. et al., 2002. Seismic attenuation performance of the first prototype of a geometric anti-spring filter. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* 487(3), pp. 652-660.
Cella, G. et al., 2005. Monolithic geometric anti-spring blades. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* 540(2-3), pp. 502-519.
Chen, D. et al., 2014. Vibration measurement in the KAGRA cryostat.. *Classical and Quantum Gravity,* 31(22), p. 224001.
Creighton, T., 2008. Tumbleweeds and airborne gravitational noise sources for LIGO. *Classical and Quantum Gravity,* 25(12).
Cumming, A. V. et al., 2021. Proposed large scale monolithic fused silica mirror suspension for 3rd generation gravitational wave detectors. *arXiv preprint arXiv:2111.09119.*
Dahl, K. et al., 2012. Suspension platform interferometer for the AEI 10 m prototype: concept, design and optical layout. *Classical and quantum gravity,* 29(9), p. 095024.
DeSalvo, R., 2007. Passive, nonlinear, mechanical structures for seismic attenuation. *Transactions of the ASME, Journal of computational and non-linear dynamics,* pp. 290-298.
DeSalvo, R., Blow, J., Pineda Bosque, C. & Selleri, S., 2022. Angled beam expander telescopes for the Michelson beams in third generation gravitational wave observatories. *Classical and Quantum Gravity,* 39(4).
Harms, J., 2019. Terrestrial gravity fluctuations. *Living reviews in relativity* .
Harms, J. et al., 2010. Characterization of the seismic environment at the Sanford Underground Laboratory, South Dakota. *Classical and Quantum Gravity* , 27(22), p. 225011.
Harms, J. et al., 2021. Lunar Gravitational-wave Antenna. *The Astrophysical Journal,* 910(1).
Hild, S. et al., 2009. A xylophone configuration for a third-generation gravitational wave detector. *Classical and Quantum Gravity,* 27(1), p. 015003.
Hoek, E., Brown, E. T. & ASCE, M., 1980. Empirical strength criterion for rock masses. *Journal of the geotechnical engineering division,* 106(9), pp. 1013-1035.
Hua, W. et al., 2004. Low-frequency active vibration isolation for advanced LIGO. *In Gravitational Wave and Particle Astrophysics Detectors,* Volume 5500, pp. 194-205.
Jani, K. & Loeb, A., 2021. Gravitational-wave Lunar Observatory for Cosmology. *Journal of Cosmology and Astroparticle Physics,* 2021(June 2021).
Karsten, D and the LISA study team, 1996. LISA: laser interferometer space antenna for gravitational wave measurements. *Class. Quantum Grav,* 13(A247).
Kawamura, S. et al., 2006. The Japanese space gravitational wave antenna—DECIGO. *Classical and Quantum Gravity,* 23(8).
Khalaidovski, A. H. G. C. D. et al., 2014. Evaluation of heat extraction through sapphire fibers for the GW observatory KAGRA. *Classical and Quantum Gravity,* 31(10), p. 105004.
Kirchhoff, R. et al., 2020. Local active isolation of the AEI-SAS for the AEI 10 m prototype facility. *Classical and Quantum Gravity,* 37(11), p. 115004.
Lognonné, P. et al., 2021. *Lunar Seismic and Gravitational Antenna (LSGA).* [Online] Available at: https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087607031744010&userAction=Browse&templateName=&documentId=a315450fae481074411ef65e4c5b7746
[Accessed 29 January 2022].

Losurdo, G. et al., 1999. An inverted pendulum preisolator stage for the VIRGO suspension system. *Review of scientific instruments,* 70(5), pp. 2507-2515.
Marka, S. et al., 2002 . Anatomy of the TAMA SAS seismic attenuation system. *Classical and Quantum Gravity,* 19(7), p. 1605.
Marvin, A. & Lantz, B., 2013. *Enhanced Feed-Forward Control for Advanced LIGO,* s.l.: LIGO Document T1300907-v1.
Milazzo, E., 2022. *Private communication.* s.l.:s.n.
Naticchioni, L. et al., 2020. Characterization of the Sos Enattos site for the Einstein Telescope. *Journal of Physics: Conference Series,* Volume 1468, p. 012242.
ORFEUS, 2022. *Observatories & Research Facilities for European Seismology.* [Online]
Available at: http://orfeus-eu.org/
[Accessed 3 January 2022].
Reitze, D. et al., 2019. Cosmic explorer: the US Contribution to gravitational-wave astronomy beyond LIGO. *arXiv preprint arXiv:1907.*
Sannibale, V. et al., 2008. Recent results of a seismically isolated optical table prototype designed for advanced LIGO. *In Journal of Physics: Conference Series* , 122(1).
Saulson, P. R., 1994. Seismic Noise and VibrationIsolation. In: *Fundamentals of interferometric gravitational wave detectors.* s.l.:World Scientific, pp. 127-142.
Stochino, A. et al., 2009. The Seismic Attenuation System (SAS) for the Advanced LIGO gravitational wave interferometric detectors.. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 598(3), pp. 737-753.
Tshilumba, D. et al., 2014. Vibration analysis and control of the LIGO observatories large chambers and support piers. *PROCEEDINGS OF ISMA2014 INCLUDING USD2014*, pp. 187-200.
Virdone, N. et al., 2008. Extended-time-scale creep measurement on Maraging cantilever blade springs. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 593(3), pp. 597-607..
Wannenmacher, H., 2021. *Private communication.* Austria: mplenia.
Wanner, A. et al., 2012. Seismic attenuation system for the AEI 10 meter Prototype. *Classical and quantum gravity*, 29(24), p. 245007.