Characterization of the Virgo seismic environment

T Accadia 1, F Acerese 2a, P Astone 3a, G Ballardin 4, F Barone 2ac, M Barsuglia 5, A Basti 1ab, Th S Bauer 7a, M Bebronne 1, M G Beker 7a, A Belletti 5, M Bitossi 6a, M A Bizouard 9a, M Blom 7a, F Bondi 9b, L Bonelli 1ab, R Bonnand 10, V Bosch 8a, L Bosi 11a, B Bouhou 3, S Braccini 8c, C Bradasca 1a, M Branchesi 12ab, T Briant 3a, A Brillet 9a, V Brisson 8a, T Bulik 14bc, H J Bulten 7ab, D Buskulic 4, C Buy 5, G Cagnoli 12a, E Calloni 2ab, B Canuel 1, F Carbognani 3, F Cavalieri 8a, R Cavalieri 1, G Celli 6a, E Cesarini 12b, O Chiab 9a, E Chassande-Mottin 5, A Chincarini 15, A Chiummo 2a, F Cleva 9a, E Coccia 16ab, F-P Cohadon 13, C N Colacino 6ab, J Colas 4a, A Colla 3ab, M Colombini 9b, A Conte 13ab, M Coughlin 17, J-P Coulon 9a, E Cuoco 4, S D’Antonio 16a, V Dattilo 4, M Davier 8a, R Day 4, R De Rosa 2a, G Debreczeni 18, W Del Pozzo 7a, M del Prete 19c, I Di Fiore 2a, A Di Lieto 6ab, M Di Paolo Emilio 16ac, A Di Virgilio 6a, A Dietz 7a, M Drago 19ab, G Endrőczi 18, V Fafone 6ab, I Ferrante 6ab, F Fidecaro 6ab, I Fiori 1, R Flaminio 10, L A Forte 2a, J-D Fournier 13, J France 2a, S Frasca 1ab, F Frasconi 16ab, M Gallimberti 10, L Gammaioni 1ab, F Garufi 2ab, M E Gaspár 5, G Gemme 4, E Genin 1, A Gennai 2a, A Giacotto 5, R Gouaty 1, M Granata 5, C Greverie 1a, G M Guidi 12ab, J-F Hayau 5, A Heidmann 11, H Heitmann 5, P Hello 4, P Jaranowski 14d, I Kowalska 14ab, A Królak 14ac, N Leroy 1a, N Letendre 1, T G F Li 1a, N Liguori 19ab, M Lorenzini 12a, V Loriette 8b, G Losurdo 10, E Majorana 3a, I Maksimovic 8a, N Man 9a, M Mantovani 5ac, F Marchesoni 11a, F Marion 1, J Marque 4, F Martelli 12ab, A Masserot 1, C Michel 10, L Milano 6ab, Y Minenkov 16a, M Mohan 4, N Morgado 10, A Morgia 16ab, S Mosca 2ab, B Mours 1, L Naticchioni 3ab, F Nocera 1, G Pagliaroli 16ac, L Palladino 16ac, C Palomba 3a, F Paololetti 4a, M Parisi 2a, A Pasqualetti 1, R Passaquieti 6ab, D Passuello 6a, G Persichetti 2ab, F Piergiovanni 12ab, M Pietka 14ab, L Pinard 10, R Poggiani 16ab, M Prato 15, G A Prodi 19ab, M Punturo 11a, P Puppo 3a, D S Rabeling 2ab, I Rácz 18, P Rapagnani 3ab, V Re 16ab, T Regimbau 9a, F Ricci 3ab, F Rohmer 5a, A Rocchi 16a, L Rolland 1, R Romano 2ak, D Rosińska 14c, P Ruggeri 4, B Sassolas 10, D Sentenac 4, L Sperandio 16ab, R Sturani 12ab, B Swinkels 4, M Taccia 4, L Taffarello 19c, A Tonelli 7ab, M Tonelli 6ab, O Torre 19ac, E Tournelé 13a, F Travasso 11ab, G Vajente 6ab, J F J van den Brand 7ab, C Van Den Broeck 19a, S van der Putten 7a, M Vasuth 18, M Vavoulidis 8a, G Vedovato 19c, D Verkindt 1, F Vetrano 12ab, A Vicere 12ab, J-Y Vinet 9a, S Vitale 17a, H Vocca 8ab, R L Ward 3, M Was 8a, M Yvert 1, A Zadrożny 14c, and J-P Zendri 19c

1 Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74944 Annecy-Le-Vieux, France
2 INFN, Sezione di Napoli; Università di Napoli ‘Federico II’ Complexo Universitario di Monte S. Angelo, I-80126 Napoli; Università di Salerno, Fisciano, I-84084 Salerno, Italy
3ab "to be inserted"
The Virgo gravitational wave detector is an interferometer (ITF) with 3 km arms located in Pisa, Italy. From July to October 2010, Virgo performed its third science run (VSR3) in coincidence with the LIGO detectors. Despite several techniques adopted to isolate the ITF from the environment, seismic noise remains an important issue for Virgo. Vibrations produced by the detector infrastructure (such as air conditioning units, water chillers/heaters, pumps) are found to affect Virgo’s sensitivity, with the main coupling mechanisms being through beam jitter and scattered light processes. The Advanced Virgo design seeks to reduce ITF couplings to environmental noise by having most vibration-sensitive components suspended and in vacuum, as well as muffle and relocate loud machines. During the months of June and July in 2010, a Guralp-3TD seismometer was stationed at various locations around the Virgo site hosting major infrastructure machines. Seismic data were examined using spectral and coherence analysis with seismic probes close to the detector. The primary aim of this study was to identify noisy machines which seismically affect the ITF environment and thus require mitigation attention. Analyzed machines are located at various distances from the experimental halls, ranging from 10 to 100 m. An attempt is made to measure the attenuation of emitted noise at
the ITF and correlate it with the distance from the source and with seismic attenuation models in soil.

PACS numbers: 04.80.Nn, 07.05.Kf, 95.55.Ym

(Some figures may appear in colour only in the online journal)

1. Introduction

The general theory of relativity predicts that all accelerating objects with non-symmetric mass distributions produce gravitational waves (GW)\textsuperscript{20}. LIGO (the Laser Interferometer Gravitational-Wave Observatory) \cite{1} and Virgo \cite{2} experiments seek to directly detect GWs and use them to study astrophysical sources.

Virgo, located in Cascina, Italy, consists of a laser Michelson interferometer with 3 km long, Fabry–Perot resonant optical cavities in its arms. With respect to other similar detectors, Virgo has enhanced sensitivity between 10 and 100 Hz due to the seismic isolation performance of the ‘super-attenuators’ to which the test masses are suspended \cite{3}. Beginning in 2011, the detector expects to undergo upgrades, known as Advanced Virgo (AdV), to improve its sensitivity by one order of magnitude \cite{4}.

Seismic noise places a limit on Virgo’s detection sensitivity. In particular, the main source of seismic noise in the 10–100 Hz band at the Virgo site is the detector’s infrastructure machines (see figure 1 (left) for a comparison with a low-noise model). Although Virgo’s mirrors are well isolated from a local seismic activity by suspension systems made up of multi-stage pendulums, seismic noise remains a concern. The residual ground motion causes ‘diffused light’ \cite{5}. Because of unavoidable imperfections in the detector’s optical components, some tiny fraction of light can exit the main optical path and strike a surface that is connected to the ground, and thus be subject to the local seismic field. When this light scatters off objects connected to the ground (such as optical components on external tables used for detector controls), it is often diffused over a wide solid angle. A fraction of the light can re-enter the main beam path, but with a noisy phase modulated by the seismically excited scattering object. This phenomenon functions as additional noise in the GW channel and limits its sensitivity.

Because seismic events couple in this way into the GW channel, it is necessary to understand and attenuate the noise from the local seismic environment. Many of the strong lines seen during VSR2 can be attributed to seismic sources (see figure 1 (right)). To assist in the identification effort, the Virgo detector is supplemented with several types of environmental sensors, including seismometers and accelerometers, that monitor the local environment \cite{6}. These channels are used to detect environmental disturbances that can couple to the GW channel and are placed in sensitive areas of the interferometer. To reduce the influence of anthropogenic noise, during the AdV upgrade, machines that are identified as seismically and acoustically affecting the interferometer will be replaced, moved, or isolated \cite{4}. The current proposal is to move all chillers, water pumps, air compressors, and air conditioners from their current locations to other areas farther from the interferometer. By placing these machines on their own isolated platforms and by adopting techniques to reduce noise emission and propagation, Virgo hopes to significantly reduce their effects on the detector. To prioritize the actions required to reduce noise at Virgo, a careful documentation of the present local

\textsuperscript{20} As presented at the Gravitational-Wave Physics and Astronomy Workshop in Milwaukee, Wisconsin, 26–29 January, 2011.
seismic environment is necessary, as well as identification among the infrastructure machines of relevant sources of seismic noise reaching the detector’s sensitive components. The work described hereafter is part of this effort.

During the months of June and July in 2010, a Güralp-3TD seismometer was stationed to monitor floor vibrations at various technical areas around the Virgo site, which host several infrastructure machines (i.e. water chillers, heaters, pumps, etc). The power spectra of the measured seismic data were examined, and several single sources were identified using correlation of the seismic data with synchronous records of the infrastructure machines working status (i.e. temperature monitors, voltage sniffers, etc). Then, seismic data were correlated with the synchronous record of permanent seismic probes close to the detector. Studying the calculated coherence and power spectra, we selected ‘relevant’ sources whose noise emissions reach the detector and measure the noise attenuation between the sources and detector. We also measured approximate noise reduction factors as a function of the distance between the machine and the detector.

Section 2 discusses the methods used when taking and analyzing data. Section 3 describes examples of noise emissions from the sources found in this analysis at various locations. Section 4 provides an estimate for the attenuation of the noise spectral peaks as a function of distance. Section 5 presents our conclusions.

2. Characterization methods

2.1. Measurement setup

We acquired several sets of data with a Güralp CMG-3TD tri-axial seismometer [8] at six locations around the site. The Güralp CMG-3TD is a portable three-component broadband seismometer with a flat velocity response over the 0.0083–100 Hz frequency band. The chosen sampling rate was 250 Hz. The Güralp seismometer is equipped with a GPS antenna receiver.
Figure 2. Left: aerial view of the Virgo interferometer. Right: aerial view of Virgo’s central area. Measurement sites are marked with letters (see table 1).

Table 1. Locations of seismometer placement.

| Section letter | Test probe location | Reference probe location | Distance between seismometers (m) |
|----------------|---------------------|--------------------------|----------------------------------|
| A              | Technical Building 1: ground floor | Central Building: ground floor | 80                               |
| B              | Building 1: first floor | Central Building: ground floor | 105                              |
| C              | Outside Building 1: ground floor | Mode Cleaner: ground floor | 30                               |
|                | Outside Mode Cleaner Building: ground floor | Mode Cleaner: ground floor | 10                               |
| E/F            | West/North End Building: ground floor | West/North End Building: external optical bench | 20 |
Table 2. Important noise lines identified in the study. The line’s frequency, periodicity, source, and the ratio of the PSDs of the test and reference probes are given.

| Location                  | Frequency (Hz)   | Periodicity (period) | Source                   | PSD ratio |
|---------------------------|------------------|----------------------|--------------------------|-----------|
| Technical Building 1      | 24.2, 48.4, 78.6 | Periodic (42 min)    | Cold-water chiller 1     | 16        |
| Building 1                | 19.3             | Continuous           | Computer fans            | 13        |
| Outside Building 1        | 48.9             | Continuous (daytime) | B1 chiller               | 2         |
| Mode Cleaner              | 48.9, 97.8       | Periodic (21.5 min)  | Mode Cleaner chiller 2   | 220       |
| West End Building         | 47.1             | Continuous           | Warm-water pump          | 1.1       |
| West End Building         | 48.8             | Continuous           | Cold-water pump          | 6.1       |
| North End Building        | 22.8             | Continuous           | Water pump               | 4.2       |

three-axis velocimeter with a flat response over the 0.1–200 Hz frequency band. If the source is not obvious, suspected machines are analyzed with a piezoelectric accelerometer placed in direct contact with the machine and read out with a spectrum analyzer. This piezoelectric accelerometer is a PCB model 393B12 single-axis accelerometer with flat response in the range from 1 Hz to 1000 kHz. The machines characteristic frequencies are then compared to those seen in the coherence.

2.2. Analysis methods

We considered the relevant frequency lines (persistent spectral peaks) that appear as significantly coherent (coherence rising out of the background) between the test and the reference probes, as the source of those lines is very likely to be the same. Coherence itself does not allow one to distinguish between the seismic signals generated close to the test probe (i.e. machinery under test) from those produced close to the reference probe (i.e. cooling fans of electronic units). In order to determine when the former is the case, the ratio of the test and reference seismometers PSDs is examined, and coherent lines that are stronger near the reference probe are selected. These techniques work well for machines producing continuous lines, such as water pumps and cooling fans.

Periodic lines, on the other hand, are more difficult to identify. Because the lines come and go, they tend to be washed out in PSD averaging. For this reason, the frequency–time plots of the PSDs are produced and examined by eye for periodic lines. In order to identify the source of these lines, we compute the root mean square (RMS) around that line, which is defined as

\[
\text{RMS} = \sqrt{\frac{1}{f_2-f_1} \sum_{i=f_1}^{f_2} x_i^2 \cdot \delta f},
\]

where \(x_i\) is the \(i\)th component of the frequency band in question and \(\delta f\) is the width of the frequency bins in the spectrum. The sum goes from \(i = f_1\) to \(i = f_2\), where \(f_1\) and \(f_2\) are the minimum and the maximum frequencies, respectively, in the frequency band. This RMS value is then correlated with the time series of various infrastructure machine-monitoring system (IMMS) signals, including temperature and pressure probes.

3. Characterization examples

In this section, the most significant examples utilizing methods discussed above are presented. In table 2, information about important, identified noise lines are given.
3.1. Characterization of noise from Technical Building 1

A data set was taken in Technical Building 1 (TB1) and compared with data from a seismometer on the floor of the Central Building (CB), where the two arms of the interferometer converge. These two probes are approximately 80 m apart. The PSDs of the test and reference probes, as well as the coherence between them, can be seen in figure 3. A periodic line around 24.2 Hz (with harmonics at 48.4 and 72.6 Hz) is seen, which is shown in detail in figure 4 (left).

The coherence for this line between the test and the reference probes was about 0.6, indicating a relevant correlation between the two seismometers at that frequency. In order to find the source of the periodic line, it was necessary to determine in which building the line was louder. The ratio of the PSDs (seismometer in TB1/seismometer in CB) was approximately 16, indicating the source of the line to be in TB1.

The time series of several machinery monitors in TB1 were compared with the RMS of the 24.2 Hz signal in the Güralp seismometer, one of which can be seen in figure 4 (right). From this figure, the RMS is clearly correlated with the time series of a temperature monitor.
of the first water chiller. We see that when the temperature of the water reaches a high point, the cold-water chiller switches on, causing the temperature of the water to decrease. When the temperature reaches a low point, the water chiller switches off and the whole process starts again. The chiller is located on the roof of TB1. Even though the chiller is equipped with insulating springs, the vibrations can probably travel through the rigid water pipes between TB1 and CB or in the water itself.

3.2. Characterization of noise from the cold-water chiller outside the Mode Cleaner

Another data set was taken outside the Mode Cleaner Building (MCB), on the same concrete platform as the MC’s cold-water chiller, and compared with the seismometer on the MCB floor. The MCB contains the end mirror of the Input Mode Cleaner, an optical cavity that filters jitter and power noise as well as higher order modes from the beam. The distance between these probes is approximately 10 m.

In viewing the PSD plots, a number of significant lines are noticed. This includes continuous lines at 24.2 and 38.8 Hz and a strong periodic line at 48.9 Hz, which has a harmonic at 97.8 Hz. To study this line, the RMS around the 48.9 Hz band was computed and compared to probes inside the MCB. A water temperature probe follows this line well, as can be seen in figure 5, indicating its source is the MC water chiller. This line is important since coherence was noted at its frequency between the GW channel of VSR2 run data and the seismometer in the MCB (see figure 1 (right)). Thus, it seems that the MCB water chiller affects the Virgo sensitivity and, for this reason, requires prompt attention for noise reduction.

3.3. Characterization of noise in the West End Building

Another data set was taken inside the West End Building (WEB) near the machinery and compared with an Episensor seismometer located on the external optical bench. The distance between these seismic probes is approximately 20 m.

Analyzing the PSD plots, we noted several significant lines, including continuous lines at 24.7, 47.1 and 48.8 Hz. 47.1 and 48.8 Hz are associated with the ‘warm’- and ‘cold’-water pumps, respectively, as verified with the piezoelectric accelerometer in figure 6. As the 47.1 Hz signal reached the optical bench with almost no attenuation, there is likely a preferred path, e.g., through water pipes, which must be investigated further.
Figure 6. This plot shows the PSD for both the warm- and cold-water pumps in the WEB. The data were taken with the piezoelectric accelerometer in direct contact with the machines under study. The warm-water pump’s PSD has a strong line around 47.1 Hz, which is shown by the red star on the left. The cold-water pump’s PSD exhibits a strong line around 48.8 Hz, which is shown by the blue star on the right.

Figure 7. A plot of the average of the PSD ratio of the coherent lines as a function of distance between the probes. The soil quality factor ($Q = 20$) and phase velocity ($v = 200 \text{ m s}^{-1}$) of surface shear waves have been measured at Virgo, as reported in [9]. We selected locations separated by at least a few wavelengths of soil. The attenuation factors data at 105 m are lower limits only.

4. Attenuation measurement

Using the above results, we seek to measure how much noise attenuation occurs when a machine is on its own foundation and a certain distance away from an experimental area. The PSD ratio of test and reference probes is used as a tentative estimate of the attenuation of the vibration, the result for which can be seen in figure 7. Measurements are compared to
a dissipation law accounting for geometrical spreading of surface cylindrical waves and for energy dissipation in soil (see [9] and references therein).

As can be seen in the plot, distances of about 30 m or less have an attenuation of approximately a factor of 3, while distances of about 80 m and greater have attenuation values greater than 10. Indeed, the simple noise attenuation model does not apply in most of the examined cases. One reason is that the point-like source approximation is not valid for short propagation distances \(d \leq \lambda\), with our seismic waves length \(\lambda \approx 10\) m or for extended sources \(L \geq d\), with the machine platform size \(L \approx 10\) m). In addition, the soil medium is often not uniform, and waves’ reflection and refraction can occur at discontinuities. Wave amplification due to mechanical resonances of the two platforms (technical and experimental areas) which are excited by the seismic noise is also possible. Another important reason is that in most cases propagation does not occur uniquely through soil. Less-dissipative paths can exist, such as through water pipes or pressure waves inside the water itself.

5. Conclusion

Noise from several Virgo infrastructure devices, such as water chillers, heaters, and pumps, seismically affects sensitive parts of the interferometer. Although an impact on the present interferometer is not evident in Virgo’s sensitivity (with the exception of the MC chiller), the noise reaching the experimental area is, in several cases, considerably above the background and requires a reduction for the AdV.

Measured attenuation of seismic signal from a distant source seems not compatible with the much stronger attenuation expected from soil dissipation. It is suspected that water pipes might function as seismic shortcuts and thus need more comprehensive investigation and mitigation attention. Noise transmitted through soil can be more efficiently reduced using seismic isolation systems (i.e. springs).

Further beneficial studies might include setting up a noise source with the known power and characteristic frequencies at various distances from a sensitive experimental area. This would allow a comprehensive study of the noise attenuation as a function of distance, something we were unable to do in this study.

Acknowledgments

This project was funded by the NSF through the University of Florida’s IREU program. The authors acknowledge the support from Italian Ministero dell’Istruzione, dell’Università e della Ricerca through grant PRIN 2007NXMBHP.

References

[1] Abbott B et al (LIGO Scientific Collaboration) 2009 Rep. Prog. Phys. 72 076901
[2] Acernese F et al (Virgo Collaboration) 2008 Class. Quantum Grav. 25 114045
[3] Braccini S 2005 Astropart. Phys. 23
[4] Acernese F et al (Virgo Collaboration) 2008 Virgo Internal Report VIR-0089A-08 (https://tds.ego-gw.it/ql/?c=2110)
[5] Accadia T et al (Virgo Collaboration) 2010 Class. Quantum Grav. 27 194011
[6] Barone F, Garufi F and Milano L 2001 VIRGO Document VIR-MAN-NAP-5800-102 (https://tds.ego-gw.it/ql/?c=800)
[7] Peterson J 1993 Open-File Report 93–322
[8] Boschi V and Gennai A 2010 VIRGO Document VIR-0172A-10 (https://tds.ego-gw.it/ql/?c=7305)
[9] Saccorotti G et al 2011 Bull. Seismol. Soc. Am. 101 568–78