Innovations in seismic sensors driven by the search for gravitational waves

Mark Beker[1], Xander Campman[2], Jules van Oven[1], Wim Walk[2], Jack Levell[2], Zijian Tang[2], Mike Danilouchkine[2], Dirk Smit[2], Johannes van den Brand[3], Soumen Koley[3], and Maria Bader[3]

Abstract

An example is provided of how technology from a seemingly far-removed field of science has found its way into seismic surveying equipment. In order to achieve affordable dense sampling to remove adverse seismic-noise effects from gravitational-wave measurements, autonomous, integrated seismic nodes were developed for flexible deployment around the gravitational-wave detector's key components. The required sensitivity is achieved by utilizing a high-sensitivity, 5 Hz geophone in combination with a low noise recording channel, resulting in a self noise of < 1 ng/√Hz at 1 Hz. This specification is also promising for low-frequency single-sensor passive and active seismic acquisition. Ninety-six nodes were deployed during a field trial to demonstrate various novel passive seismic techniques for subsurface and microearthquake characterization using dense surface arrays. This showed the value of an affordable and practical dense surface array in extracting useful subsurface information from seismic noise and characterizing small earthquakes. The nodes were shown to have the long battery life required to be practical in their intended, showing only 50% battery consumption after a 21-day survey at high-gain setting.

Introduction

In the past few decades, seismic surveying has seen technological enhancements made possible by engineering advances on both the source and receiver side. There is a growing realization that dense sampling can significantly improve image quality (Regone et al., 2015). This has led to a trend toward high-productivity point-source, point-receiver land seismic surveys. One of the drivers for this trend is the operational benefit that can be gained by deploying large spreads of single sensors. This increased efficiency, in turn, makes high trace densities affordable. A similar trend is visible in passive seismic data acquisition. The availability of more affordable, sensitive, low-power, autonomous sensors makes it economically and operationally more attractive to deploy dense surface arrays instead of sparse downhole sensors for microseismic and fracture monitoring, for example.

The recently reported experiments to detect gravitational waves from merging black holes may seem far removed from seismic surveys but have led to substantial improvements in seismic-receiver efficiency. In turn, the experiences gained by exploration companies in characterizing and processing passive seismic data have the potential to improve the low-frequency sensitivity of future gravitational-wave detectors.

In this article, we discuss technology originating from gravitational-waves research conducted at the National Institute for Subatomic Physics (Nikhef) in the Netherlands that led to a new seismic sensor system. We describe how gravitational-wave detectors can be improved by monitoring ambient seismic noise and extracting subsurface information from it. We then describe a vault test to establish the integrated nodes' electronic noise floor. Finally, a seismic field trial is discussed in which we tested various passive seismic processing technologies for subsurface and microearthquake characterization using dense surface arrays.

From spinning black holes to spin-off technology

Nikhef scientists, and their global collaborative community, are reveling in the wake of this year's monumental discovery: the first observation of a gravitational wave (Abbott et al., 2016). The detection has been rated as one of the biggest scientific discoveries of the century and comes exactly 100 years after Albert Einstein first theorized the existence of such waves.

The detected gravitational waves were produced by a pair of spiraling and colliding black holes. Despite the enormity of the wave's source, the effects here on earth are almost infinitesimal: the stretching and squeezing of space caused by the gravitational wave amounts to a relative distance change of 10^{-18} m (a thousandth of the width of a proton!) in an apparatus several kilometers across.

To detect such minute vibrations, great care must be taken to isolate the detectors from external noise sources — for example, from seismic rumblings from distant earthquakes or passing traffic. These seismic disturbances couple to a gravitational-wave detector in two fundamental ways. First, ground motion mechanically transforms to unwanted vibrations of the detector components. This seismic noise is combated using elaborate vibration-isolation systems. Second, seismic motion produces fluctuating density variations in the surrounding soil that result in minute variations in the local gravitational field.

This latter effect, known as gravity gradient noise, is more elusive (being far below the detection limit of gravity gradiometry) and is impossible to shield mechanically. Nevertheless, research shows that if the ground motions surrounding the gravitational-wave detector's crucial components can be adequately sampled, their effects could be subtracted from the instrument's output by determining their corresponding density fluctuations (Beker, 2013). However, this requires the construction of a velocity model below the site of the detector in order to be able to predict the propagating waves and their effect on density fluctuations. Fortunately, this can be performed using seismic near-surface velocity inversion, well known in the seismic industry, using measurements of the same ambient seismic noise to be compensated. These measurements are performed in a bandwidth similar to that used in high-resolution seismic imagery.

Simulations of the expected noise levels of the Advanced Virgo gravitational-wave detector are shown in Figure 1. The

[1]Innoseis B.V.
[2]Shell Global Solutions International B.V.
[3]National Institute for Subatomic Physics, Nikhef.

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gravity gradient noise is plotted as a spectral variation based on the level of measured seismic activity at the Virgo site. It shows that gravity gradient noise is expected to limit the sensitivity of the detector in the frequency range of a few Hz to tens of Hz.

Improving the low-frequency sensitivity of current and future gravitational-wave detectors has important scientific merit. Binary systems, like the black holes described above, linger for longer at these lower frequencies, meaning that with seismic noise compensation, more accurate information can be extracted from their gravitational waveforms.

The required performance of the seismic sensors exceeded what was cost effectively available in the market to sample the seismic wavefield around the detectors with sufficient density. This set in motion a development in novel sensor technology as well as a means to quickly and cost effectively measure seismic vibrations with high-density flexible arrays. Cost-effective, high-density arrays of seismic sensors are also sought after in the seismic exploration industry where there is a growing interest in more efficient surveys, which may be realized with single-sensor recording.

Innoseis leveraged the technology and knowledge from fundamental gravitational-wave research to develop an ultralow-power and therefore lightweight and long-endurance autonomous seismic recording system called Tremornet. A partnership with Shell was forged early on to fine-tune the technology toward the seismic industry's requirements. Such collaboration accelerates product development and, in turn, allows Nikhef's scientists to more quickly reapply the technology to their own physics experiments.

Vault noise test results

After extensive testing in the lab, verification of the Tremornet nodes was done in cooperation with the Royal Netherlands Meteorological Institute (KNMI). Seismic measurements were performed at the KNMI Heimansgroeve seismic observatory near Epen in the Netherlands from 11 to 25 November 2015. The objective of the experiment was to verify the performance of Tremornet sensors by comparing the recordings with the KNMI Streckeisen STS-1 seismometer. In addition, the relatively low seismic background noise and stable measuring conditions allow the application of the three-channel correlation technique (Sleeman et al., 2006). This is particularly useful when verifying the self-noise performance of seismic sensors that have an integrated architecture.

Figure 2 gives a summary of the results. The spectra are calculated from 20-second stretches of data that were windowed with a Blackman-Harris window and then averaged. The transfer function of the respective sensors was used to convert the sensor output to equivalent ground-motion input. A comparison can be made up to 12.5 Hz, as this is roughly the bandwidth of KNMI's STS-1 data.

From Figure 2, we see excellent agreement among the various sensors. It can also be observed that the three-channel correlation technique allows us to accurately extract the sensor self-noise levels. These results show that the sensor self noise is less than 1 ng/√Hz at 1 Hz and as low as 0.1 ng/√Hz at the sensor resonance frequency of 5 Hz.

Field trial results

An early opportunity for a field test presented itself during a trial in Europe in which Shell tested various novel passive seismic techniques for subsurface and passive source characterization by deploying a dense seismic array. Ninety-six Tremornet sensors were deployed in a 100 × 100 m grid for 21 days of continuous recording. A plot of the endurance of the sensor's remaining battery charge and recorded node temperature versus time is shown in Figure 3.

While the main objective of the field trial was to collect ambient seismic noise, we also recorded a number of small earthquakes during the deployment (see Figure 4). Interpretation of the data was improved by having a large number of easily deployable stations. Because of the noise level at the surface, it is challenging to reliably determine the magnitude from a single station, as high signal to noise is required to establish a reliable magnitude estimate. Having approximately 100 sensors available, we could average the displacement spectra, after correcting for the phase differences between them, to compute an accurate fit of the average spectrum with the Brune source model (Brune, 1970).

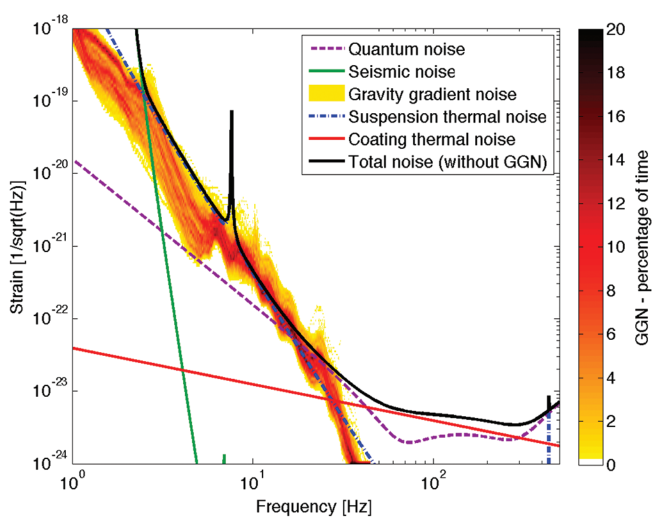

Figure 1. Simulated noise sources and sensitivity curve of the Advanced Virgo gravitational-wave detector.

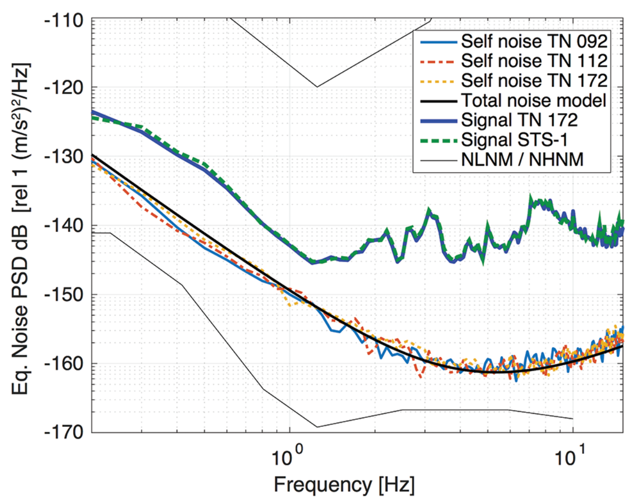

Figure 2. Performance measurement of Tremornet (TN) nodes compared against the KNMI STS-1 seismometer. The Peterson new high- and low-noise models (NLNM/NHNM) are indicated for comparison.

The result is shown in Figure 4b, where the red line is the fitted source model. The shaded area shows the spectral variation of the averaged and smoothed individual source spectra from the 96 traces, where the darker shades indicate a higher percentage of the traces occupying each bin. Showing varying spectral levels due to noise, estimates from individual traces might result in slightly different magnitudes. In this case, the time-duration of the S-wave from which the spectrum was estimated was much smaller than a second. Hence, the low frequencies are not reliably estimated and the modeled spectrum was fit to match the correct measured roll-off at frequencies approximately above 10 Hz.

The magnitude estimated from this procedure was Mw = 1.6, which coincided with the estimate from the local seismological observatory.

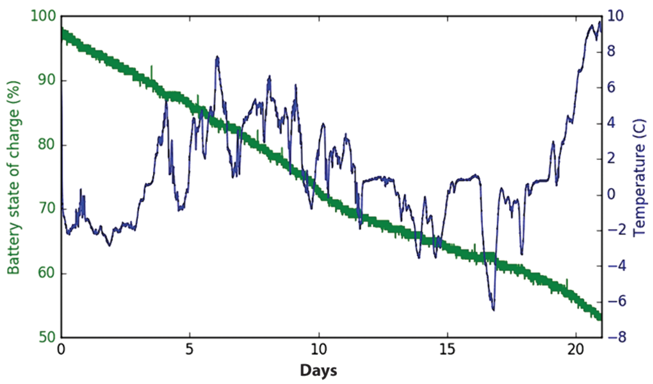

Figure 3. The temperature and battery status of a Tremornet node during a 21-day survey.

Ambient noise seismic interferometry and surface-wave inversion

The field trial's original aim was to test various passive acquisition techniques for subsurface characterization. One such method is ambient noise seismic interferometry (ANSI). ANSI aims to reconstruct the response between a receiver pair by correlating and stacking ambient noise recorded at the two receivers. The result is as if one of the two receivers were a source and the other the receiver. This response can be used to infer subsurface properties, just like shot records are used in active seismic surveys. These shot records could then be inverted to derive a velocity profile.

Interestingly, this is close to the intended use of the nodes in gravitational-wave observation where they will be used to characterize the Advanced Virgo detector site and monitor ambient seismic noise. To subtract gravity gradient noise based on surface sensor measurements, it is first necessary to build a model of the

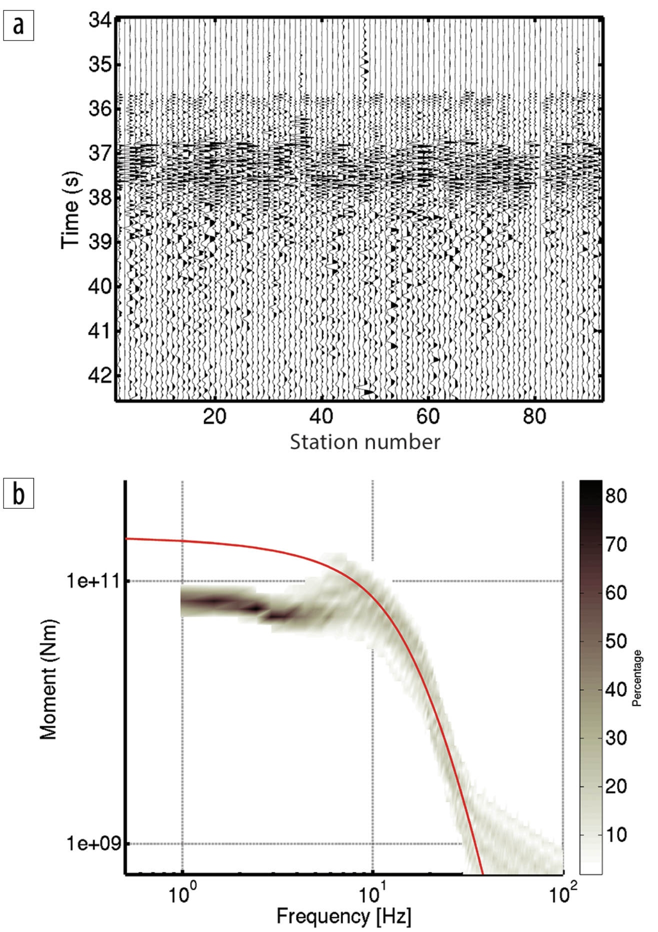

Figure 4. (a) Raw data of a magnitude 1.6 earthquake as recorded by a network of 96 Tremornet nodes. (b) The Brune source model derived by fitting the averaged spectra is shown as the solid red curve. The shaded area is the spectral variation obtained from the individual traces.

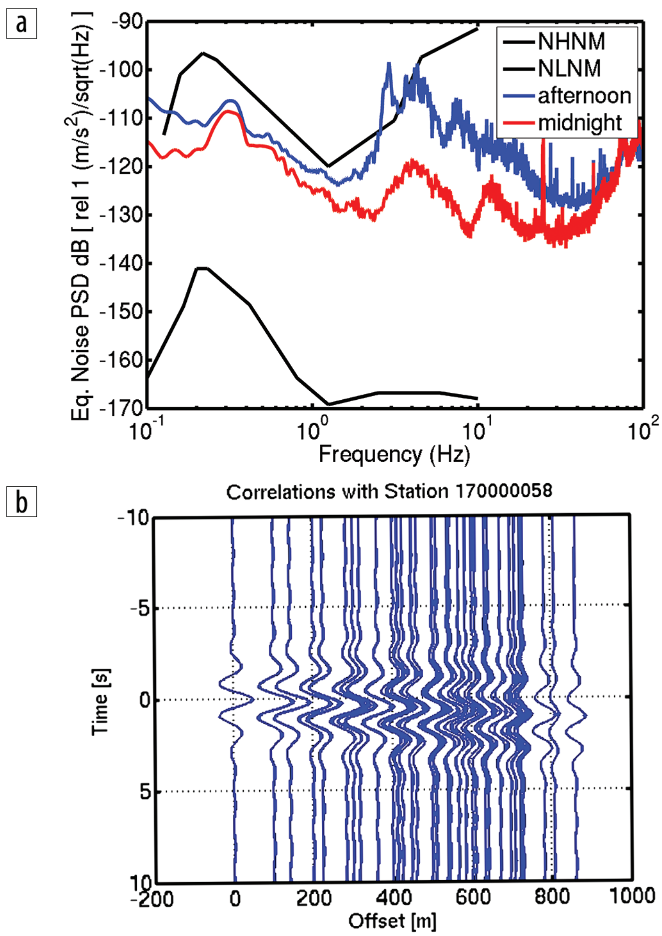

Figure 5. (a) Power spectral densities for noisy and quiet periods. (b) A virtual shot record obtained with ambient noise seismic interferometry.

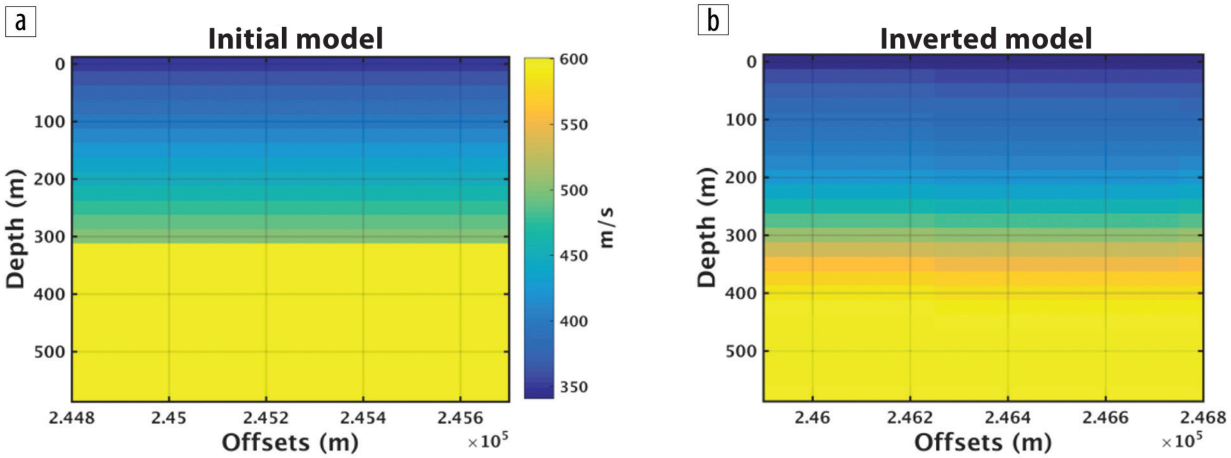

Figure 6. Near-surface inversion of shear velocity from virtual shot records obtained from ambient noise seismic interferometry. (a) Starting model. (b) Final updated model.

propagating seismic modes. After that, continuous monitoring is necessary to measure those modes and subtract them.

Figure 5a shows noise power spectral densities (PSDs) measured during one hour around midnight and one hour in the afternoon. Comparing this figure to Figure 2 shows that the ambient seismic noise levels are much higher than the intrinsic noise levels of the sensors. We also note the difference in spectral levels between midnight and afternoon in the frequency band above 2 Hz. This can be attributed to the increased daytime traffic in the area. It is also interesting to note that the two PSD curves are very similar at low frequencies. This indicates a very stable, distant source — most likely the secondary microseism.

Using 14 days of continuous noise, we apply ANSI and correlate noise recorded at all sensors with sensor number 58. After sorting to offset, we obtain the "virtual" source record shown in Figure 5b. In this way, we obtained virtual source records for all receivers in the array.

The response of these virtual sources consists of a narrow-band surface wave, indicating that the ambient noise incident on the array is dominated by low-frequency surface waves related to the peak in the PSD at around 0.4 Hz. The implication of this low-frequency content is that the surface waves are sensitive to structure at depths of several hundred meters. This is different from active surveys in which the source-output at frequencies below 1 Hz is generally very limited, and hence the surface waves are sensitive to shallower depths.

Using the narrow frequency range from 0.4 to 0.8 Hz, it was possible to invert for the local shear-velocity profile using a starting model shown in Figure 6a. The result is shown in Figure 6b. The velocity model was sensitive to information from the survey down to depths of ~400 m.

Conclusion

Gravitational-wave astronomy may seem far removed from the working grounds of seismic contractors; however, noise compensation in these fields of science and engineering have the same rigorous requirements for seismic sensors. Spin-off technology from the development of gravitational-wave detectors has led to lightweight seismic nodes with long battery life and low noise floors. Three-channel correlation techniques have been used to effectively evaluate the sensor noise floor, and it was found to be < 1 ng/$\sqrt{\text{Hz}}$ at 1 Hz. Field trials with a network of nodes were also conducted, and the sensors showed good endurance with 50% of the battery life remaining after 21 days at high gain. These trials allowed the recovery of a subsurface velocity profile useful for the subtraction of gravity gradient noise at gravity-wave observatories as well as more conventional geophysical applications. Such new technology offers the ability to effectively move to dense surface arrays for microseismic monitoring, fracture monitoring, and passive reservoir monitoring. TLE

Corresponding author: m.beker@innoseis.com

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