

1. Introduction



Figure 1 – The VIRGO Interferometer

The VIRGO experiment, located near the city of Pisa in Italy, has as its intended purpose the detection of gravitational waves (GW).¹ Other experiments of the same type include the two LIGO detectors in the USA, the GEO detector in Germany and TAMA in Japan. According to Einstein's general theory of relativity, GW are space-time ripples produced by accelerated masses. These are extremely tiny; catastrophic astrophysical events such as nearby supernovae explosions or merging of binary star systems are predicted to produce percent deformations of a unit space length by the order of 10^{-22} at most.

VIRGO is essentially a large-scale and more sophisticated version of Michelson's famous interferometer he built to detect the effects of ether. A laser beam is split by a semi-reflecting mirror and

¹ www.virgo.infn.it

sent along two orthogonal paths (called arms) of 3km each. These beams are bounced back by mirrors placed at the end of each arm. They then cross the beam splitter again and finally recombine on a photo-detector. The passage of a GW would cause a variation of the lengths of the two arms. This would cause a phase shift of the two orthogonal beams (once they are recombined) and a change of intensity of the recombined light on the photodiode. Virgo is extremely sensitive: it can detect space deformation up to 10^{-22} parts per unit length over a wide range of frequency of the GW signal, from 10Hz to 10kHz.

To achieve this level of sensitivity Virgo must be well protected from non-GW sources that could produce an accidental phase-shift of the beams. An obvious source is the shaking of mirrors because of earth motion. To prevent this Virgo's mirrors are well-isolated from ground vibration by very efficient suspension systems made of multi-stage pendulums. However, ground shaking remains a concern for Virgo. One of the major effects that can transfer ground motion to VIRGO's results is "diffused light". Because of unavoidable imperfections of the detector optical components, some tiny fraction of light can exit the main optical path and hit a surface that is seismically connected to ground (such as a wall of the vacuum chambers or lenses on external optical tables used for detector controls). The surface typically diffuses this light over a wide solid angle and a fraction of it can re-enter the main beam path but with a slightly different phase (being of course delayed due to its longer path). The beam "carries memory" of the seismic vibration of the seismic motion of the scattering surface. This light component is seen as extra noise in the detector output channel.

This explains why VIRGO personnel try to keep the environment close to the detector as quiet as reasonably possible. People walking inside buildings (where mirrors are housed), vehicles driving close to

buildings, and periodic vibrations caused by large engines (pumps, fans) are potentially dangerous and have to be avoided, if possible, or minimized. One of the main responsibilities of the scientists at Virgo is the identification and mitigation of these sources (“noise hunting”).

This summer Virgo began a roughly 6 month long science run in coincidence with LIGO. During the down time preceding this run, it was possible to investigate and analyze possible noise disturbances that would have affected the run.

The introduction of the Guralp 3TD seismometer into Virgo’s collection of tools provided an opportunity, given the 3TD’s low frequency sensitivity, to investigate noise sources to which previous Virgo seismic probes had been blind. Such sources investigated include vehicle traffic from nearby roads, machinery in Virgo’s utility building, and seismic vibrations from bridges over Virgo’s arms.

2. The Guralp 3TD Seismometer

The Guralp CMG-3TD is a weak motion broadband seismometer consisting of three orthogonal axis sensors which measure north/south, east/west, and vertical ground motion when properly oriented. The “D” in the model name denotes a model with a low-noise DM24 digitizer built in to the casing of the seismometer.

This seismometer is a “velocimeter,” that is its output is proportional to the velocity of the ground motion at the instrument location. The sensor manual claims a response range from “120s to 50Hz” and a very low intrinsic sensor noise: this sensor should be able to measure ground seismic vibrations with inverse periods from 8mHz to 50Hz in the most quiet world locations without being limited by its intrinsic noise. Figure 2 shows the seismometer and the digitizer.

The 3TD is meant to be installed on hard or well-compacted near-horizontal surfaces. The sensor must be guarded against

fluctuations in temperature, excessive airflow, and excessive vibrations. It must also be insured that the seismometer stays level to horizontal (at least within 3°) during its period of data collection. As such locations for installation must be chosen with care. Given the nature of the investigations undertaken at Virgo this summer, high quality semi-permanent installations, such as seismic vaults, were unfeasible. Instead simple installation methods were chosen that were quick to accomplish yet effective in their results.

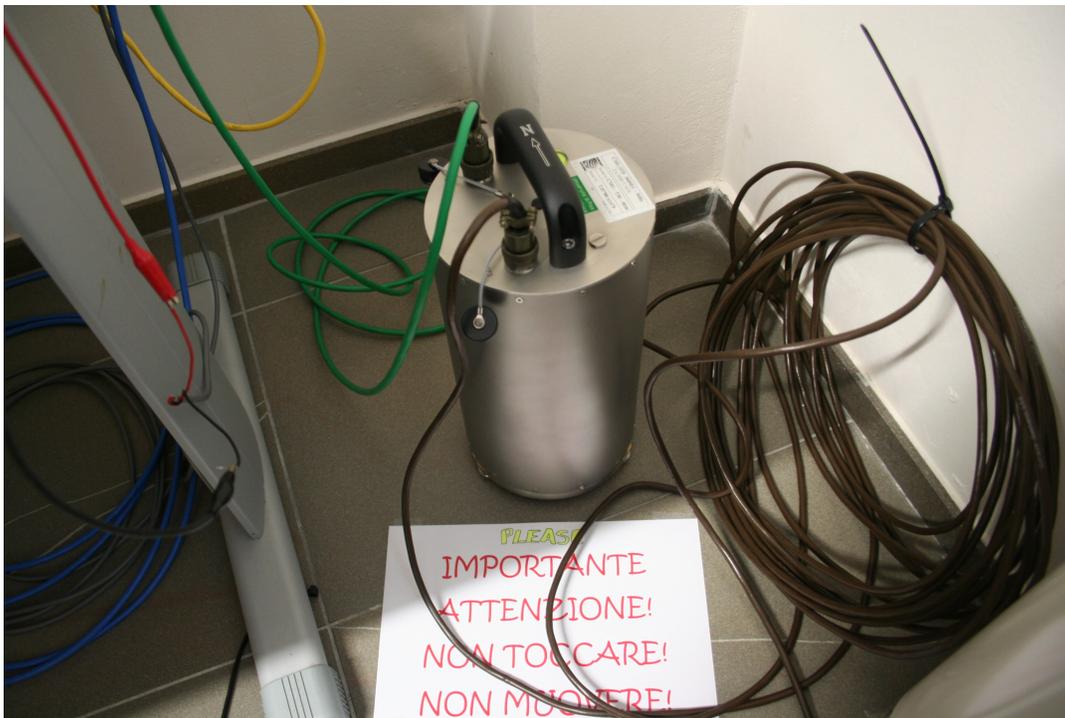


Figure 2 - The 3TD Seismometer

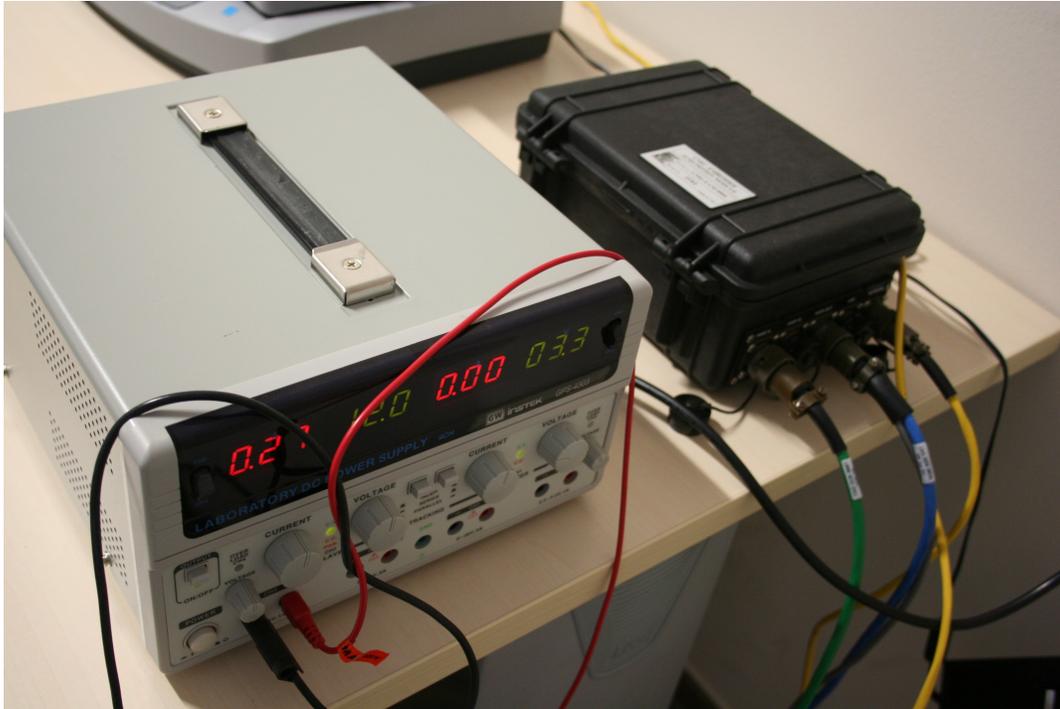


Figure 3 - A temporary power source and the CMG-EAM data collector

The basic installation approach used included a fairly deep hole (at least 10 or so centimeters above the top of the seismometer) with sand filled in a few centimeters deep at the bottom. On the sand is placed a small platform of granite, stone, or some other hard material on which to place the seismometer. The sand assisted in keeping the platform level when the actual base of the hole might not be. The seismometer is then placed on the platform in a water-resistant bag, oriented to the north arm of Virgo (which is actually about 20° off of true north) and leveled. Dirt is then slowly filled in around the seismometer. Care must be taken to avoid bumping or jarring the seismometer while this is done and the seismometer must periodically be checked to make sure that it is still level. In this manner a 3TD could be installed rapidly and still produce good quality data.

The 3TD must also be attached to a data acquisition device and a power source. At Virgo a CMG-EAM was used for data collection

and, depending on the location, a power source or battery was used. The bag must be tightly closed around the cables leading to these apparatus and folded in such a way that water does not enter. The battery and EAM must also be tightly sealed in a bag and protected against water. If the bag is good enough it is suitable to place the battery and EAM on a raised platform and fold the bag such that water does not run along the cables into the bag. A GPS antenna must also be placed near the seismometer with a clear view of the sky in order to synchronize time with GSP satellites. It must be connected to the 3TD and is waterproof.

Communication with the 3TD was quite convenient and accomplished simply by connecting a laptop via a crossover Ethernet chord. Configurations and data acquisition could then be controlled with a web interface for nearly all tasks needed. For more complex interaction an SSH connection was available.

The choices of location for each installation were made for different reasons and will be discussed in turn in this report.

3. Synchronization and Calibration

Initially the 3TD was kept on the ground in VIRGO's north terminal building. In this way it was possible to ensure the 3TD was performing well, learn its controls, collect some low-noise data and ensure that it was synchronized with VIRGO's existing sensors and calibrated properly. It was situated close to another one of VIRGO's sensors, an Episensor accelerometer (denoted by Em_SEBDNE01, 2, and 3 for each axis) installed on the external North End Bench and of course already calibrated and GPS synchronized. This provided a good opportunity to verify the new sensor calibration and synchronization.

Each Guralp 3TD is shipped already calibrated. Although

methods for performing manual calibration are available, it is usually not necessary. Each seismometer is packed with a calibration sheet to show the proper values for conversion from count output to velocity. This is different for each axis sensor and is particular to each sensor manufactured. The seismometer digitized recordings (3 channels) which are written to files in units of “counts”. The user has to convert them to meaningful velocity units (that is m/s) applying the factory calibration factors:

$$V_Z = \text{counts}_Z * 3.205\text{E-}6 \text{ [V/counts]} / 2*998 \text{ [V / m/s]}$$

$$V_{NS} = \text{counts}_{NS} * 3.216\text{E-}6 \text{ [V/counts]} / 2*1008 \text{ [V / m/s]}$$

$$V_{EW} = \text{counts}_{EW} * 3.198\text{E-}6 \text{ [V/counts]} / 2*1002 \text{ [V / m/s]}$$

This is basically a reverse of the process that digitizes the data received by the DM24 from the 3TD. It incorporates the voltage output of the seismometer for a given velocity and the count output of the digitizer for a given voltage. Counts received from the DM24 must be run through this equation in order to get useful velocity measurements for analysis.

A simple experiment was made to check the synchronization and calibration of the Guralp sensor. Since it was installed very close to another Virgo seismometer, Dr. Fiori physically jumped close to both sensors and the time of this jump was recorded. Below are the overlapped time plots of this event for both seismometers' z-axis sensors. This direction sensor was chosen for analysis because such a jump test would be most clearly seen in this axis.

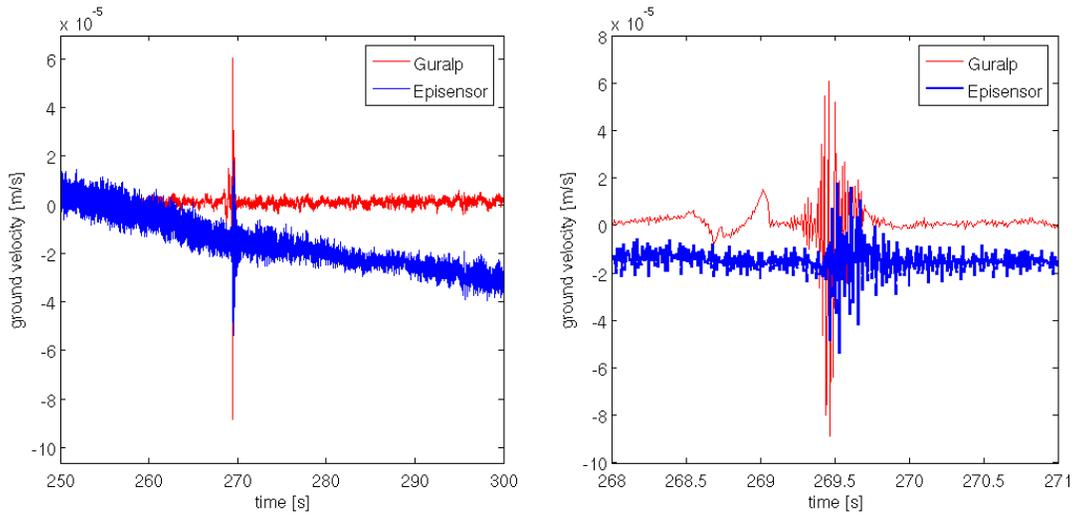


Figure 4 – Time Plots for Z-axis of both sensors during the jump test

The frequency spectra (Fast Fourier Transforms (FFT)) of the data were also computed for each sensor using Matlab.¹ The overlapped FFT's are shown below.

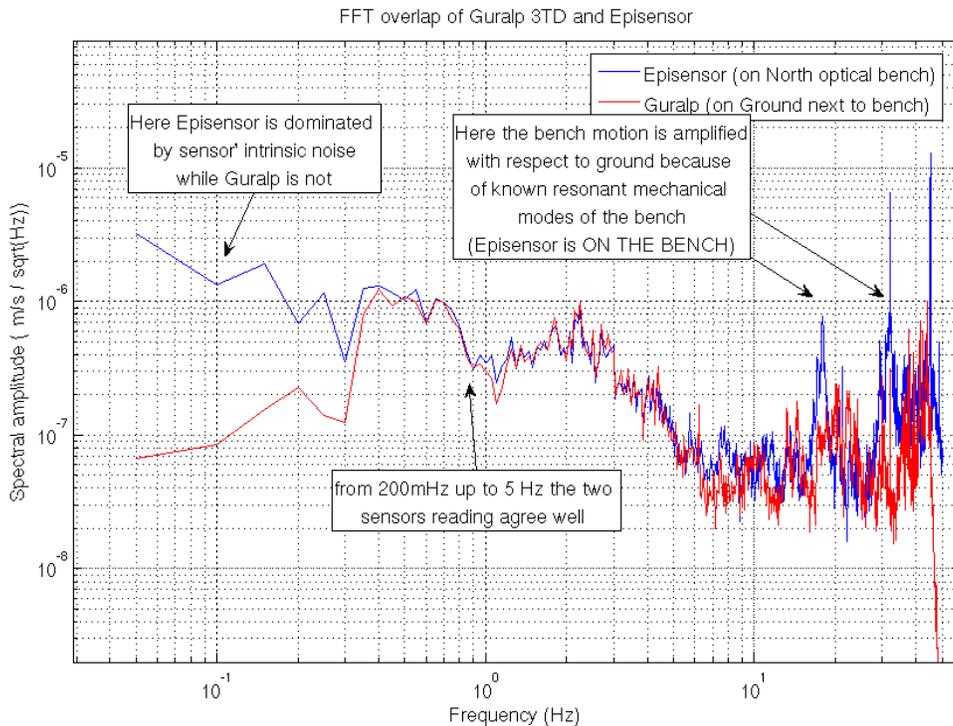


Figure 5 – FFT overlap during jump test

As described in the figure, the FFT's are synchronized where it is expected and are not as much in agreement where it is not. The

discrepancies in the FFT graphs can be explained based on the situation of the data collection.

4. RMS Wind Comparisons

The first investigation undertaken with the calibrated and synchronized 3TD was in relation to low frequency disturbances (ground motion with periods of 10s, that is 100mHz, or less) that were suspected to be due to wind. The method of investigation was trying to correlate the average amplitude of the slow ground motion measured by each 3TD sensor and wind speed data (wind speed is recorded by one anemometer on top of VIRGO offices building). The average amplitude of the ground motion in a given range of frequencies can be determined by computing the “band limited RMS” of the signal, in the following way:

$$\text{RMS}^2 = \Sigma (a_i^2 \cdot df)$$

Where: a_i is the *i-th* component of the frequency spectrum of the signal (ground velocity in this case) and df is the width of the frequency bins of the spectrum. The sum goes from $i=f_1$ to $i=f_2$, f_1 and f_2 being the boundary of the frequency interval. In our case $f_1=10\text{mHz}$ and $f_2=100\text{mHz}$.

These comparisons between the wind speed and direction detected by the anemometer probe located in Virgo’s weather station and the 3TD’s RMS signals are seen below in Figures 6 and 7.

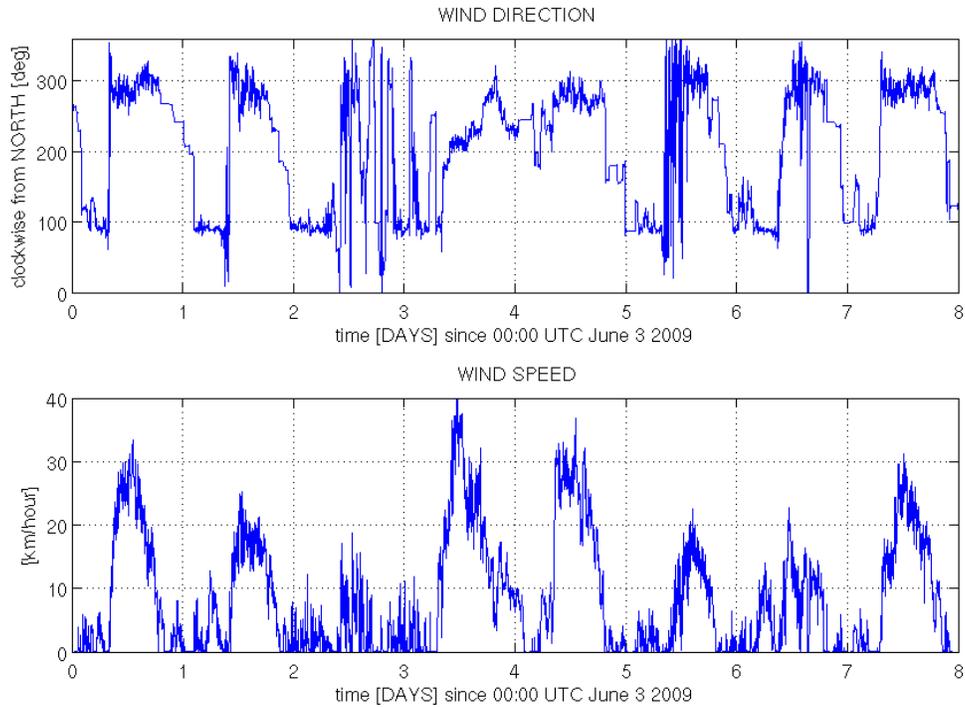


Figure 6 – Wind speed and direction over a period of one week

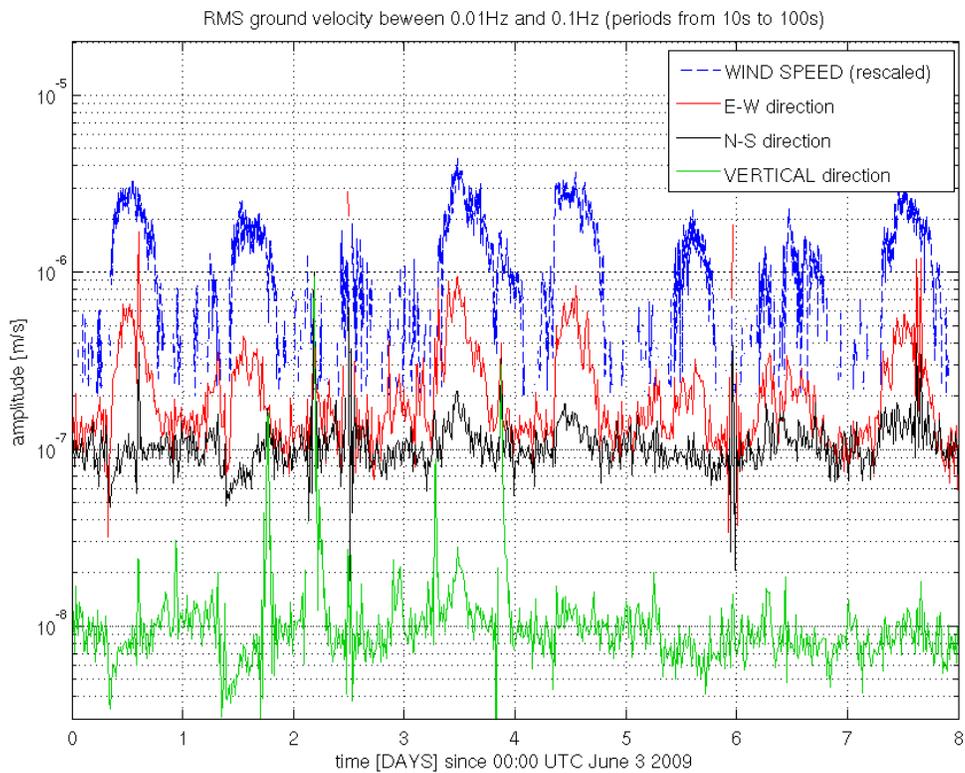


Figure 7 – Wind speed in blue is compared to the RMS signals of each

axis' sensor from the 3TD

A good visual correlation is present between the wind speed and the earth motion: the earth motion is high when the wind gets intense (wind speeds roughly above 20 km/hr). This is observed over one week of data. The data also indicate that the most intense ground motion corresponding to high wind data is measured along the E/W direction. A bit less intense (but still detectable) motion is measured along the N/S direction, while nothing is detected along the Vertical (in Figure 7). The anemometer measured the strong wind direction to be on average 300deg clockwise from North, that is West-N/W. The seismometer was located on the floor of the North Tower. We might reasonably have imagined that the ground and/or building structure to be mainly shaken along the direction of wind coming from the coast (west of Virgo) and much less along the vertical direction. This roughly corresponds to what we observed.

5. Investigation of Seismic Noise from Chillers

The first external installation of the 3TD was in between Virgo's Central Building and Tech Building, which hosts most of Virgo's utility machines (water chillers, heaters, pumps, air compressors). This location was chosen because this installation was meant to be jointly a trial run and a first investigation. It was a trial run because the seismometer was close enough to be powered without the use of batteries and because it was close enough to working offices to be serviced if needed. It was a first investigation location because of its proximity to both the Tech Building (which houses a lot of required practical machinery and therefore possible noise sources) and to the

road that runs along Virgo's north arm.

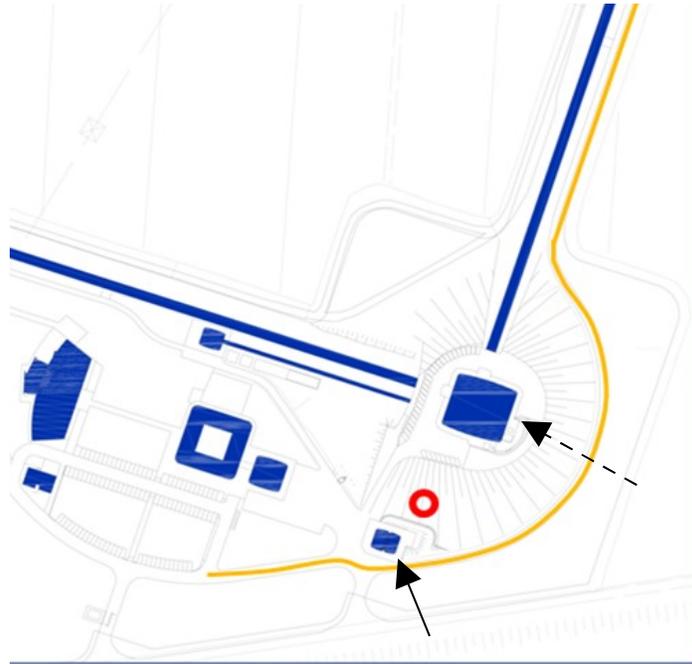


Figure 8 Aerial view of Virgo's Central Building (dashed arrow) Technical Building (solid arrow) and the first 200m of the West and North arms. Red circle indicate the Guralp installation site close to the Technical Building. In orange is the road in question.

Given its close placement to the Central Building, the seismometer's data could usefully be compared with the existing seismometer on the ground in Central Building (also a Guralp velocimeter and denoted by Em_SEBDCE04, 5, and 6 for EW, NS and VERTICAL axis respectively). The 3TD stayed at this location for about one week collecting data.

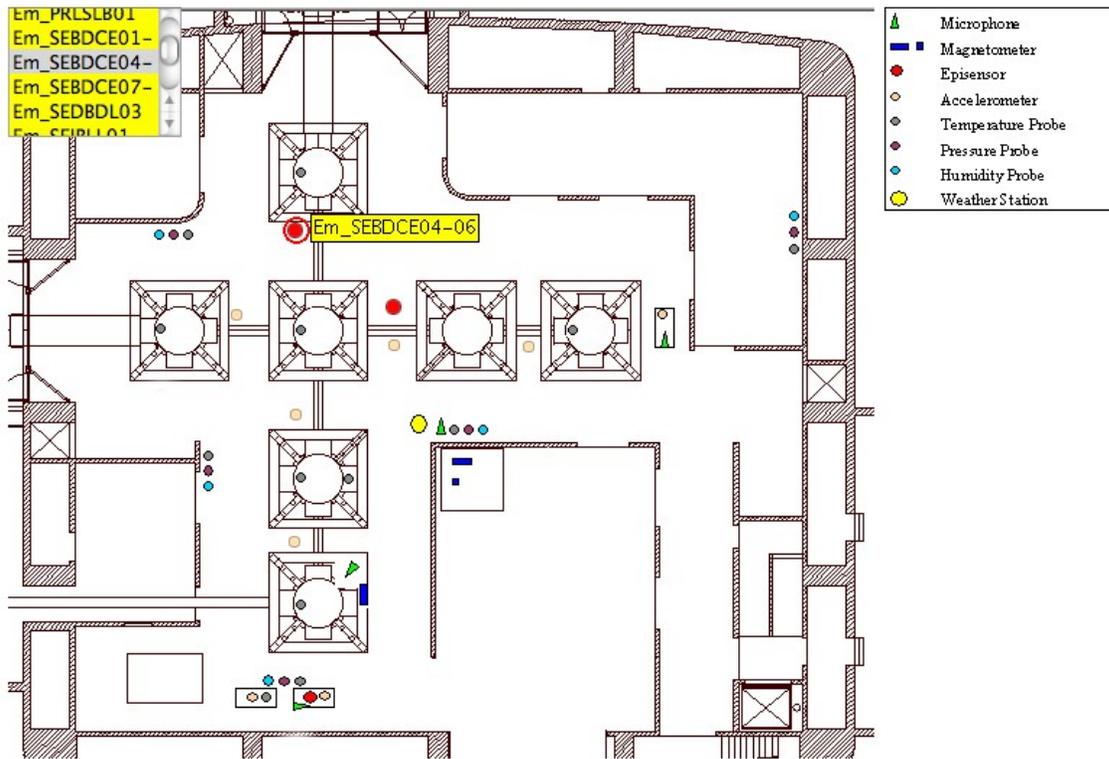


FIGURE 9 Map of the Central Building. Red circles indicate the location of the Episor seismometer.

One of the first interesting topics for investigation was an unexpected high intensity 24.2 Hz signal observed in spectrograms of the collected data. A *spectrogram* is a graph of the spectral composition of one signal as a function of time. It allows the easy visualization of the occurrence of seismic events over time. A spectrogram of the entire day of July 2nd is shown below (Figure 10), starting at midnight.

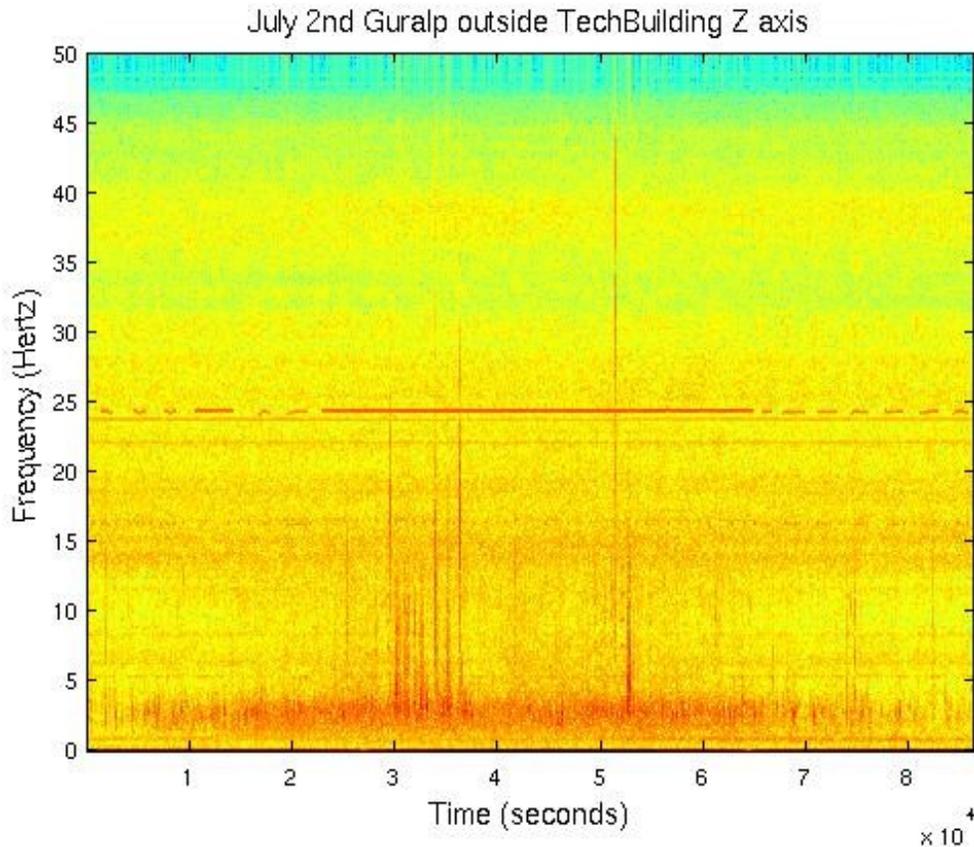


Figure 10 Spectrogram of Guralp vertical signal over 24 hours starting July 2nd at midnight. The vertical axis displays amplitude of spectral components. The color scale goes from green to yellow to red. Note the intermittent signal at 24.2Hz.

The source of this 24.2 Hz signal was a mystery. The signal was also detected inside the Central Building. This made the discovery of the source of this signal all the more desirable because it could possibly be interfering with Virgo's optics in the Central Building. Below are two spectrograms of the same period of time of both the 3TD near the Tech Building and the Guralp in the Central Building. The 24.2 Hz signal is seen in both.

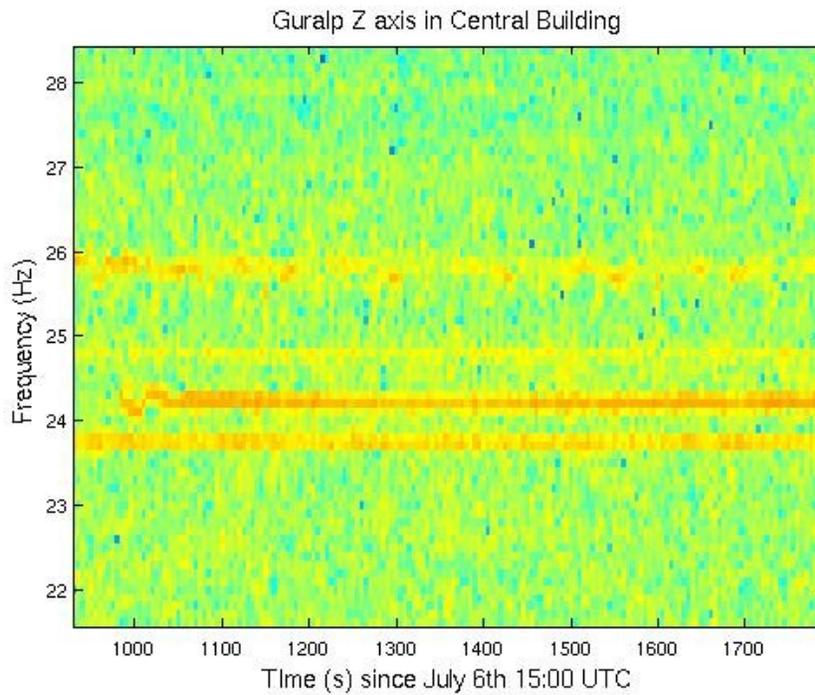
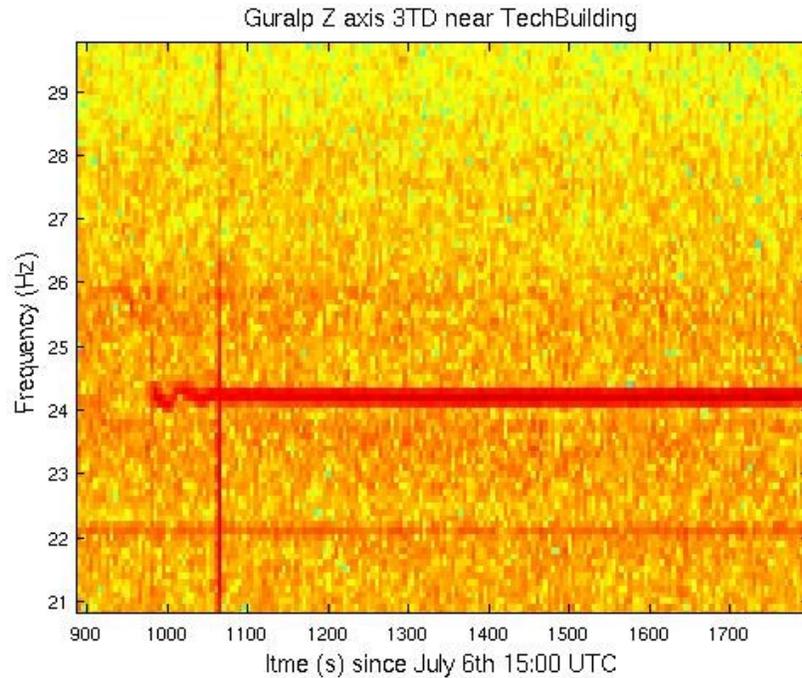


Figure 11 Top - Mystery signal detected outside Tech Building
Bottom - Signal also detected in Central Building

Given the nature of the signal starting and stopping at definite times (though not at the same time each day), and adding the fact that

the signal is seen the most intense by the 3TD closer to the Tech Bd., it was strongly suspected that the signal came from machinery in the Tech Building.

Virgo has in place numerous sensors and auxiliary controls to monitor its heating, water, and other utilities. A strong correlation is observed between a water temperature sensor and the mystery signal. This is shown in Figure 12 below. We observed that when the water temperature reaches a certain threshold value the 24.2Hz signal begins, then the temperature slowly declines, and when it crosses another low threshold, the signal ends. This temperature sensor monitors the temperature of chilled water produced by chillers in the Tech Building and sent to HVAC (heating, ventilation, and air conditioning) machines in the Central Building.

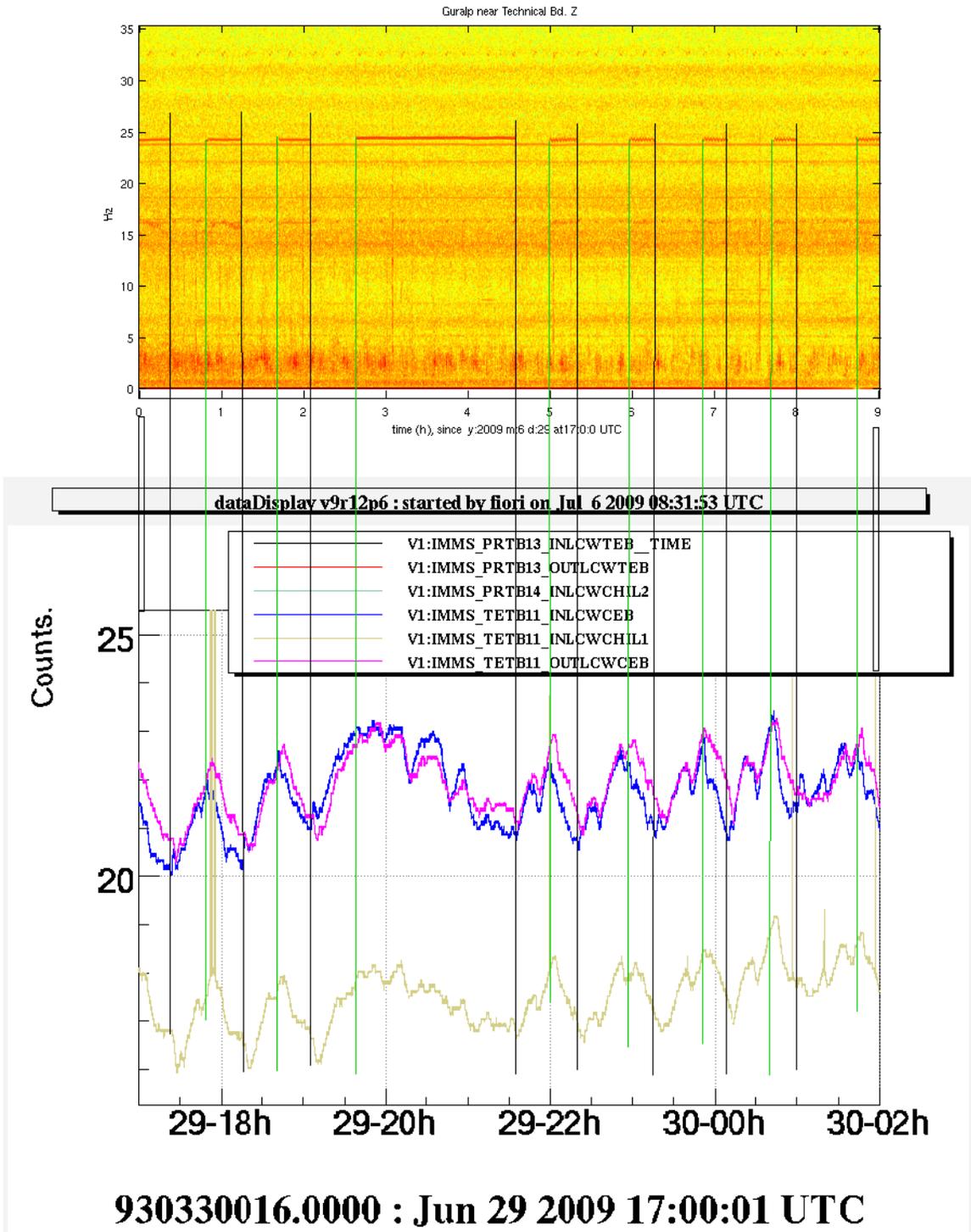


Figure 11 Top - is 9 hours spectrogram of the Guralp data recorded near to the Tech Building.

Bottom - Plot shows, over the same 9 hours, the variation of the temperature of the cold water (CW) in and out of the two chillers (CHIL1, CHIL2). Vertical lines (green/black) are added to help visualizing the correlation between the appearing/disappearing of the

24.2 Hz signal and the max/min temperatures of the cold water.

There are two water chillers on the roof of VIRGO's Tech Building: Number 1 (the newer chiller) and number 2 (the older chiller). Since either chiller could be responsible for the signal, a portable seismometer was used to analyze the exact frequency of the signals given off by both.



Figure 12 - The two water chillers (Number 2 (old) on the right, Number 1 (new) on the left) on the TechBuilding roof.



Figure 13 – The portable seismometer used.

For safety reasons the chillers could not be switched off and on at whim, so data had to be collected when opportunity struck. Not all data circumstances desired were collected but the data that was collected was enough. The collection situations include the accelerometer in between both chillers with both of them on and only chiller 1 on. Also, the accelerometer was placed directly on the frames of each to better detect their specific signal. These situations are labeled in the graph below. It is clear from these FFT overlaps that the signal around 24.2 Hz disappears when only chiller number 1 is on and it was amplified when the seismometer was placed directly on the frame of chiller number 2. The multiple peaks of this signal are labeled and appear to be harmonics of the 24.2 Hz signal.

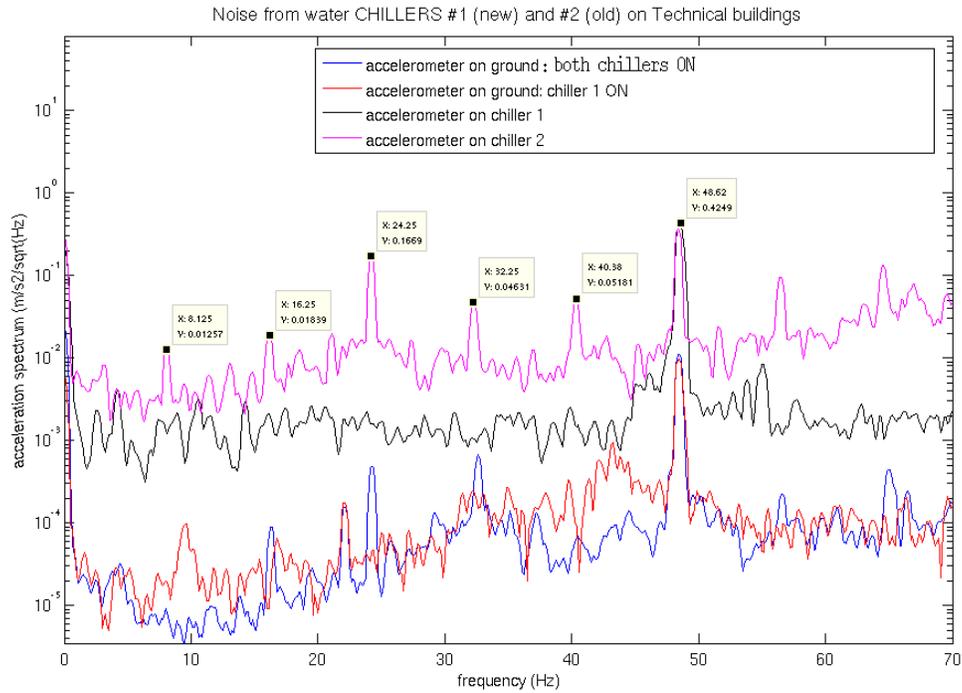


Figure 14 – FFT's of data collected by portable seismometer.

A final confirmation of the hypothesis that chiller number 2 was the culprit is provided by accidental observations of chiller number 2's turn on times. Various switch on times for the chiller were directly observed and recorded. The spectrograms were then analyzed for these times. The following is the result.

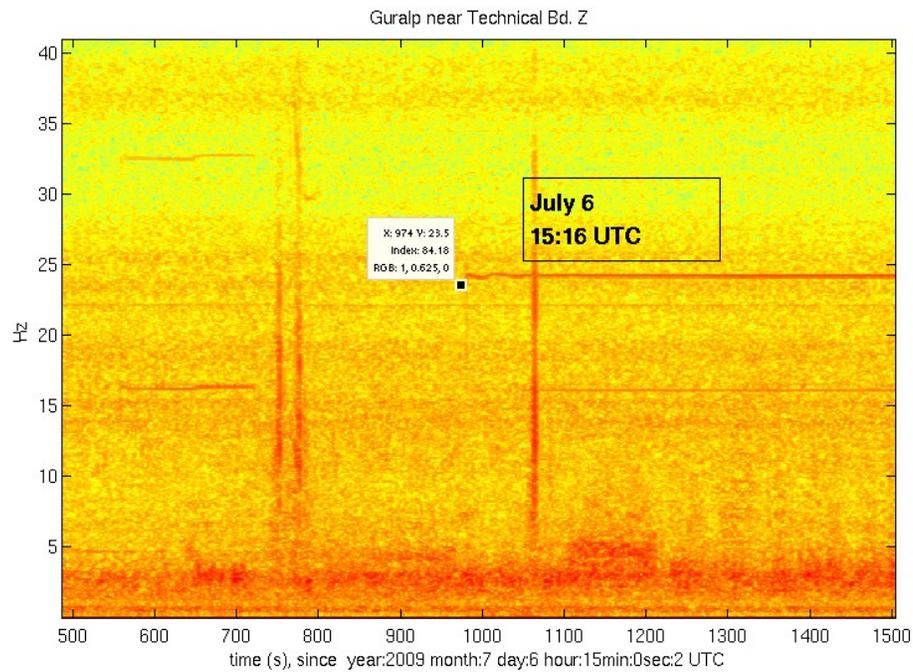
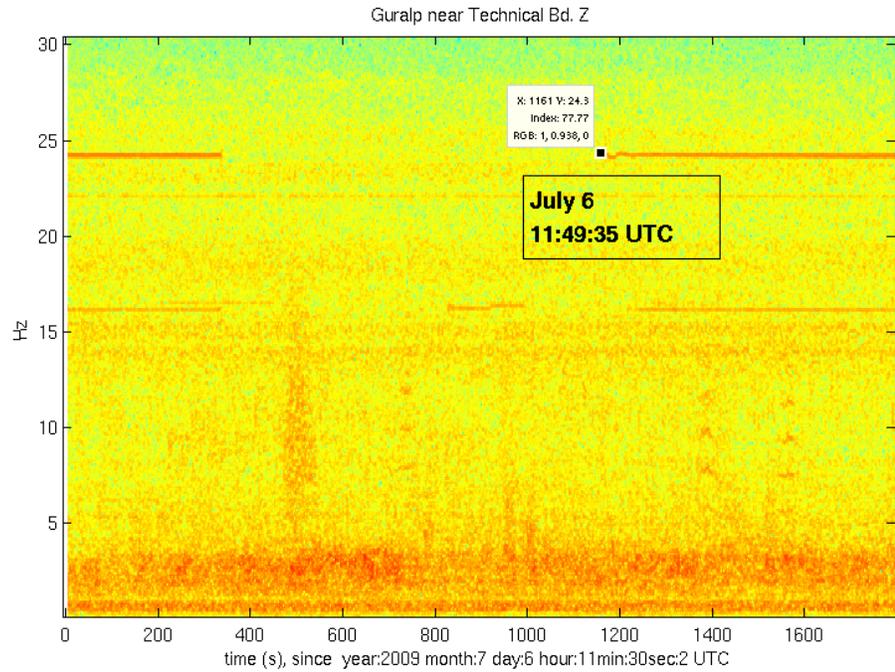


Figure 15 – Two spectrograms showing chiller number 2 switch on times.

These times were recorded as switch on times for the chiller. Upon comparison with the spectrogram it is clear that the mystery

24.2 Hz signal is provided from the old chiller 2. The seismic isolation of old chiller 2 might be improved (the springs on which the machine sits are old and possibly do not perform as well as the springs underneath the newer chiller 1). A report of this investigation was documented in Virgo's logbook for further consideration.

6. Investigation of Seismic Noise from Trucks and Cars

This installation location (next to the Tech Building) was also suitable for investigations of noise produced by traffic on the road that passes close to the Tech Building and runs along Virgo's north arm (see map in Figure 8). There was some concern about possible seismic interference with optics in the Central Building given the close proximity of the road and frequent passages of vehicles on this road.

Multiple driving tests were done with lighter cars and the heavier EGO trucks. During these tests vehicles were driving at average speed of about 40 km/hour.

What is most interesting is that some passages seem to be detected by the sensor inside too: this is evident when looking at the spectrogram (Figure 16).

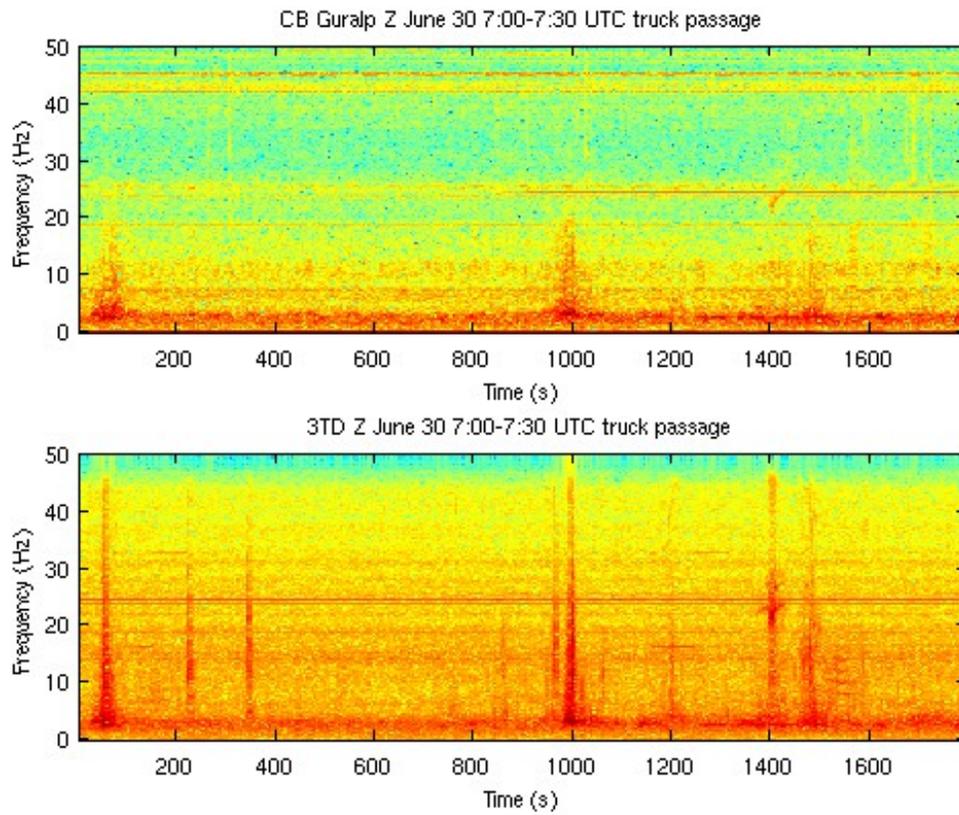


Figure 16 - Truck passages shown in spectrograms of both sensors over a half hour.

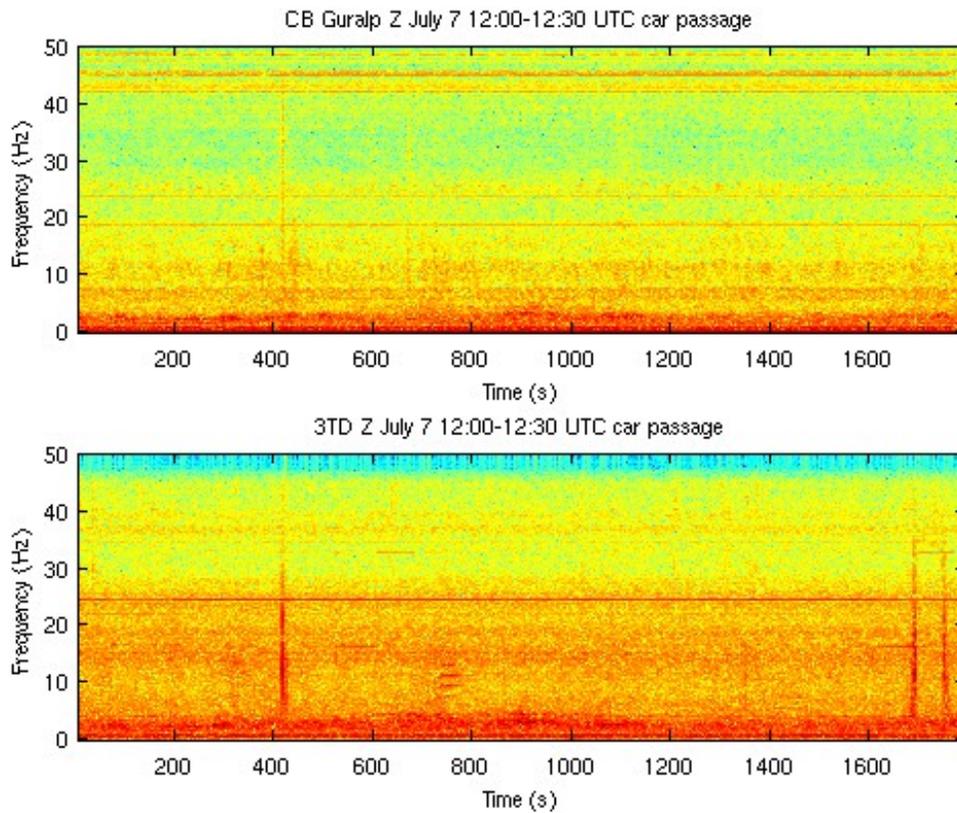


Figure 17 - Car passages shown in spectrograms of both sensors over a half hour.

Here some short seismic noise increases (like “bursts”) appear to correspond in coincidence to the most intense ones recorded by the outside sensor. These bursts appear to be of the order of 60s long, the seismic signal amplitude increasing up to a maximum then decreasing (Figure 18 is a zoom).

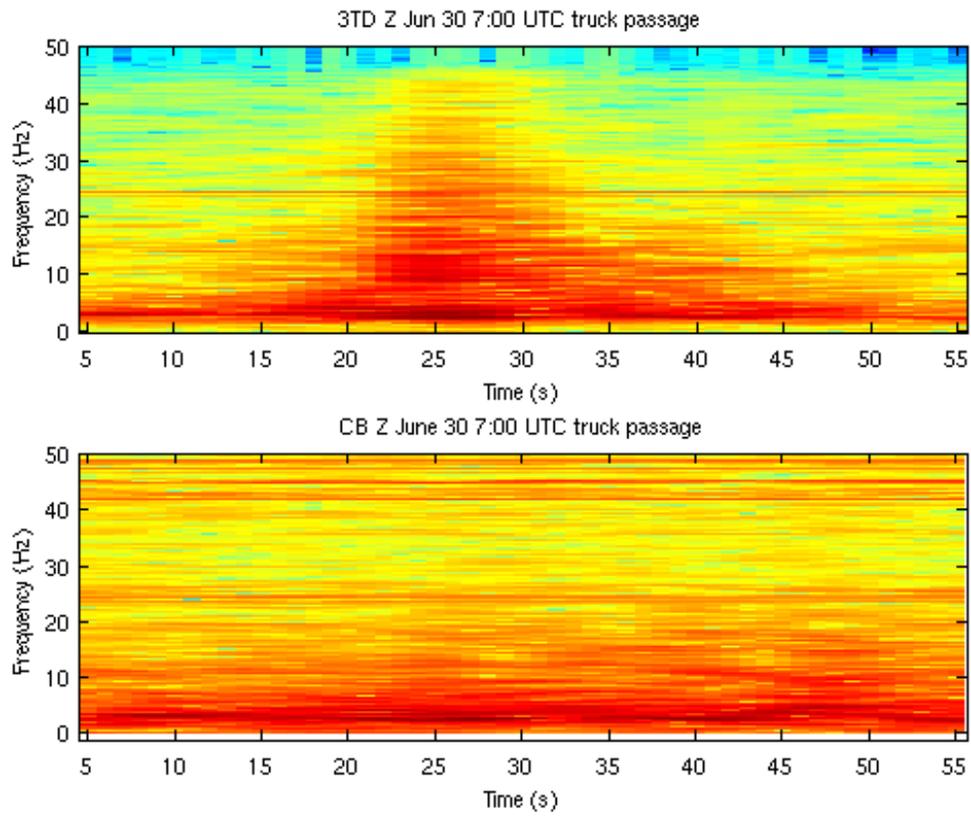


Figure 18 - A single truck passage shown in spectrograms of both sensors over 60 seconds.

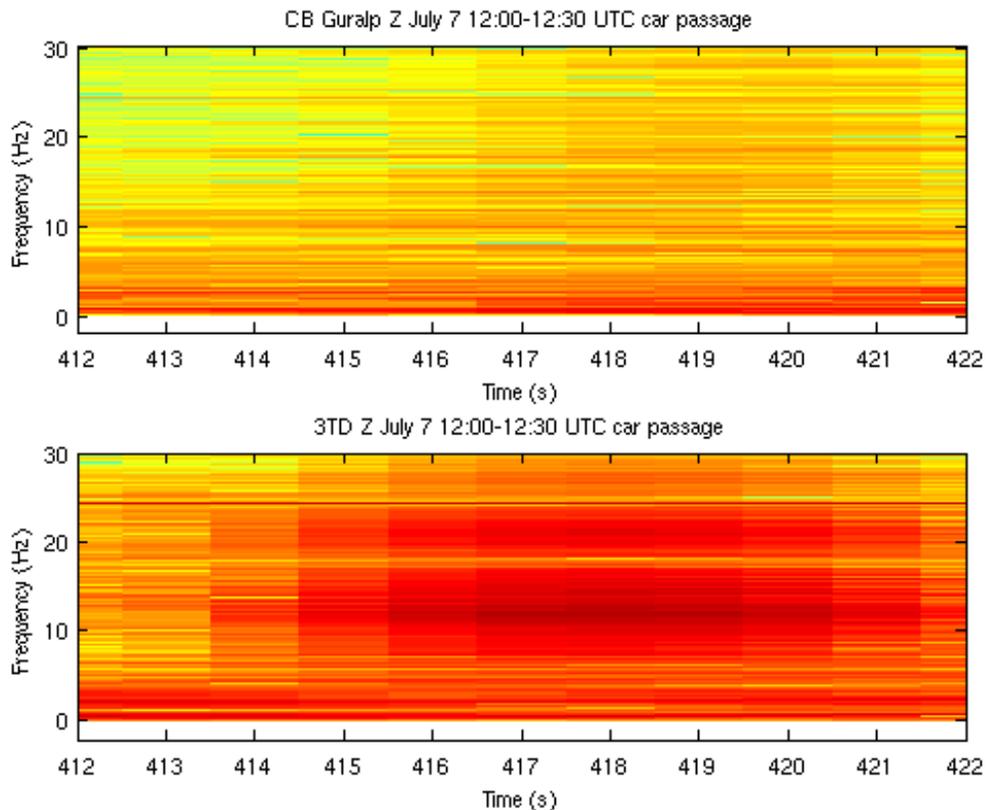


Figure 19 - A car truck passage shown in spectrograms of both sensors over 60 seconds.

Note that, while the all trucks passages seem to cause visible effects inside the Building, cars do not. The seismic noise produced by cars (which are much lighter than trucks) must be slightly above the average seismic noise inside the Building.

It is interesting to quantify the excess of seismic energy produced by vehicles outside and, especially, inside the Virgo Building. And it is interesting to compare the effect of different vehicles type.

So a time window was selected of about 60s around one seismic burst caused by an EGO truck and the car. This data's spectral composition and amplitude of the signals was then quantified by looking at the frequency spectra. These are in Figures 20 and 21.

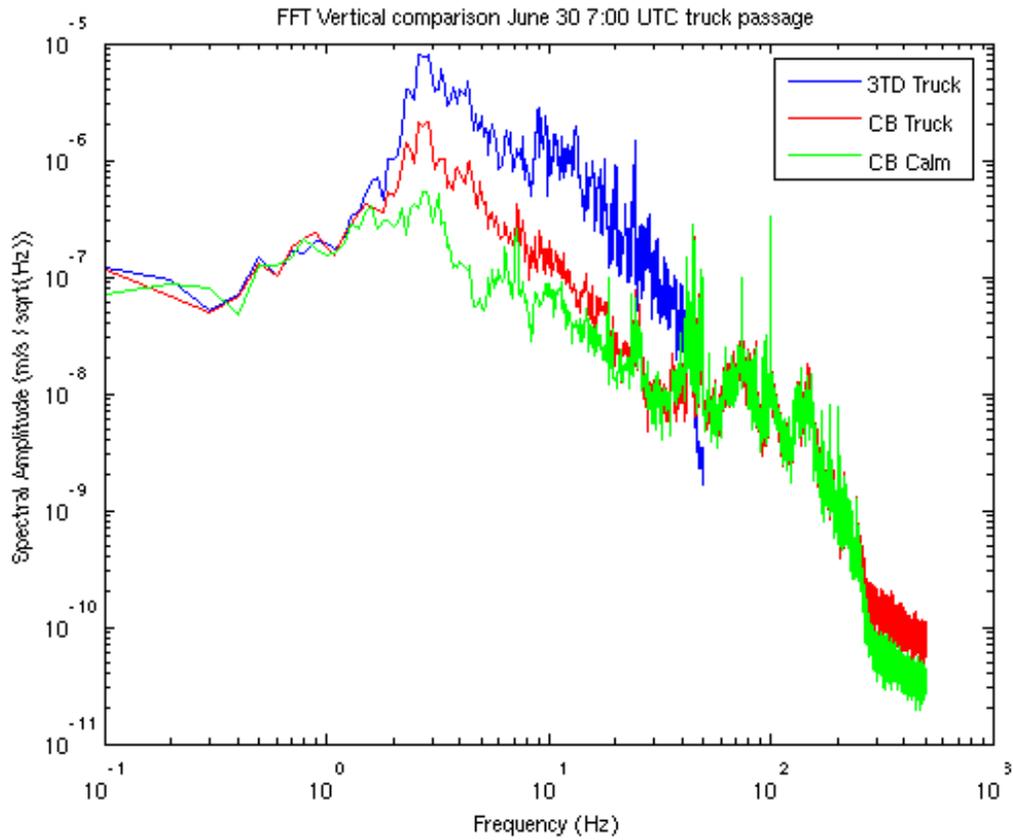


Figure 20 - FFT (60 second) overlaps showing the effects of truck passages.

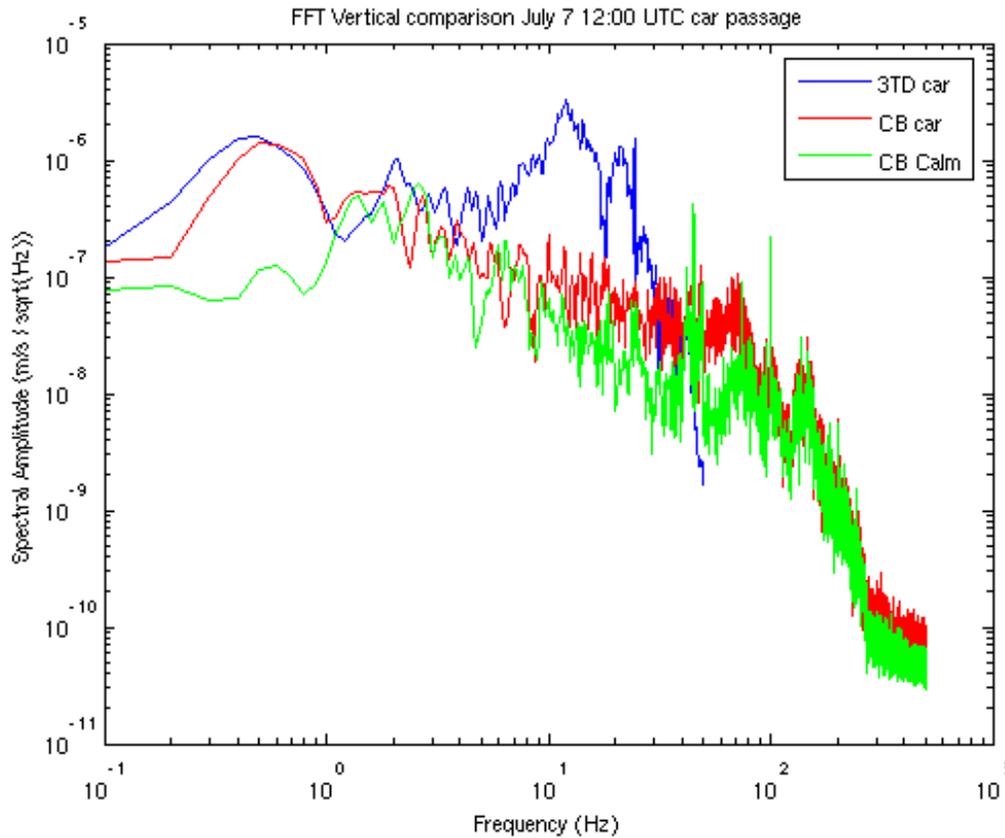


Figure 21 - FFT (60 second) overlaps showing the effects of car passages.

We see that trucks cause indeed a significant effect. The seismic noise in the Building increases around 10-20Hz, by about 5 m/s / sqrt(Hz). The car passage causes also a measurable effect, but much less than the truck passage, seismic noise increase is as well measured between 10 and 20Hz, of about 1-2 m/s / sqrt(Hz).

Since the start of the science run (July 7th) trucks are forbidden to drive along the road close to the Central Building. Car traffic is limited, but possible. In particular the security guards have to travel along this road about every 4 hours for checks of the North terminal Building. All cars have been instructed to drive at a maximum speed of 30km/hour to minimize seismic noise.

The study is to be concluded by monitoring the effect of the

slower passages during nighttime security checks (in night times the seismic noise background in the 10-20Hz region is notoriously lower, because of the lower anthropogenic noise from outside the VIRGO site area, and thus the effect of slow cars passages, if any, could be evidenced better). This monitoring will be done during the following month.

ⁱ An FFT is a method of computing a Discrete Fourier Transform (DFT) in such a way that the computations involved are greatly minimized. This efficiency can be very beneficial in digital signal processing. A DFT takes a discrete and periodic (therefore finite) signal and transforms it from the time domain into the frequency domain. This is accomplished by decomposing the input signal into a summation of sinusoidal signals. For this project Matlab was used for nearly all data analysis (except for some work done in Virgo's own dataDisplay).