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Studies of the 1-4 Hz seism

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1 Introduction

A preliminary investigation of seismic noise at Virgo site [1] has demonstrated the antropic origin of the noise in the in the 1-4 Hz frequency band. The observed features were: (i) ground motion RMS has a 24 h modulation with a minimum at about 1 AM (local time) during working days (Mon-Fri) and a reduced activity during saturdays, Sundays and holidays; (ii) the noise occurs in bursts 30-40 s long, occurring randomly at the rate of approx. 1/minute; (iii) seismic energy of bursts (measured in Virgo CB) is almost equally shared between the two horizontal components along Virgo arms, and slightly reduced (about half) along the vertical. This noise could likely be originated by the oscillations of a bridge when crossed by heavy trucks. Figure 1 shows the location of large bridges (200-500 m long) around the Virgo site: there are three such bridges at distances between 1 and 2 km from the Central and/or terminal buildings.

In section 1 of this note we describe a measurement of the oscillation frequencies of these bridges; in section 2 we describe a measurement of coincidence of seismic records taken at the bridges and simultaneously at the Virgo Central building by the on-line seismometers. The significative correlation found at one bridge provides a measurement of the bursts travel time from the bridge to Virgo CB. In section 3 we compare seismic records at the Virgo Central and terminal buildings. In section 4 we use measured delays to derive a rough extimate of the velocity of propagation of the seismic surface wave in the Virgo soil. We discuss how this velocity and above observations fit into a simple model of propagation of surface mechanic waves. Section 5 contains conlusions and suggests further studies.

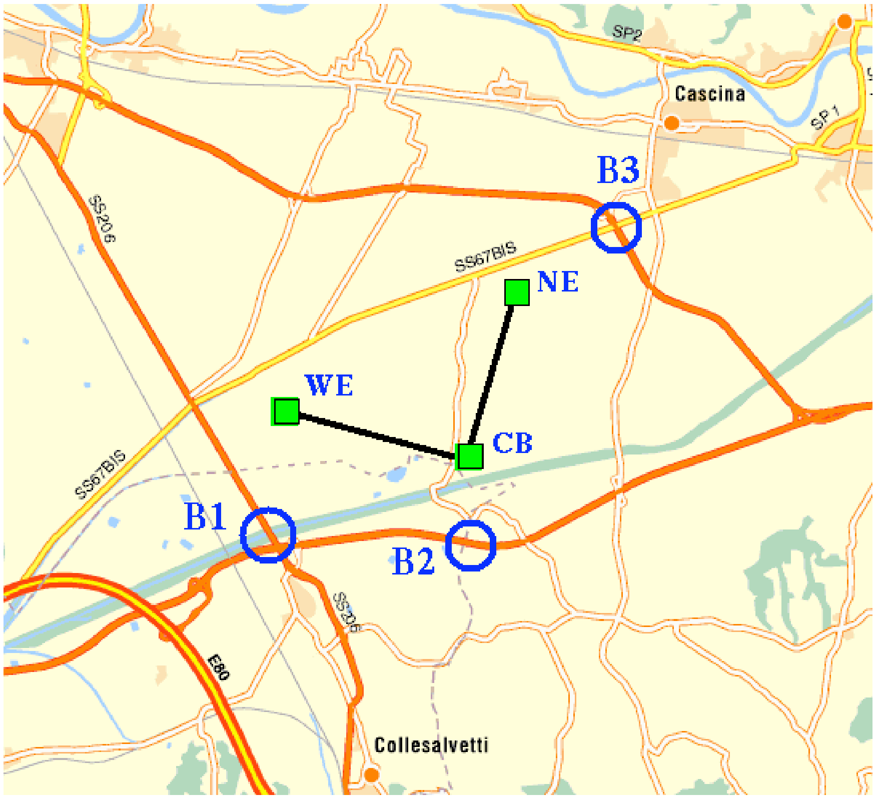

Figure 1: Location of major bridges around Virgo site. We have carried out measurements for bridges: *B1* (also named *SS-206 bridge* throughout this note) located approx. 4 km SW of Central building, and bridge *B2* (a.k.a. *Fi-Pi-Li bridge*) at approx. 1 km S of CB.

2 Measurement of bridges oscillations

Our portable equipement consisted of one vertical accelerometer (Piezotronics model 393B12 with 0.1-2000 Hz bandwidth) and a digital spectrum analyzer (ONO SOKKI CF-6400) for signal digitization, anti-aliasing filtering, amplification, and recording. Measurements were taken at bridge B1 (on SS-206 over the “canalone” ditch) and bridge B2 (on S.G.C. Fi-Pi-Li expressway, over... just fields). Bridge B1 sits on 6 concrete support pillars with approx. 25 m pitch, and a wider (50 m) central span over the ditch. The seismometer was placed on the road pavement at the bridge top. Three seismic records were taken of 80 seconds each at 25.6 Hz sampling frequency. Bridge B2 sits on 12 pillars with approx. 50 m pitch. Three seismic records (same settings) were taken with the seismometer placed on the road pavement at the bridge top, and two additional seismic records were taken underneath the bridge with the sensor placed on one of the bridge basements. Measuring time were choosen so to have either no truck crossing (only occasional cars) or some heavy trucks crossing the bridge. Figures 2, 3, 4 show the time-frequency plots of the seismic records. Bridges resonant frequencies are visible: the first one is at ≈ 2 Hz for both bridges, then at ≈ 6 and 10 Hz. Their relative amplitude seems to depend on where the seismometer was positioned at the bridge. Resonances above 10 Hz are also present (see figure 5) but here are cut by the sampling frequency used. The two bridges however differ in the duration of their oscillations, which are shorter for B1 (≈ 10 s) than B2 (≈ 30-40 s).

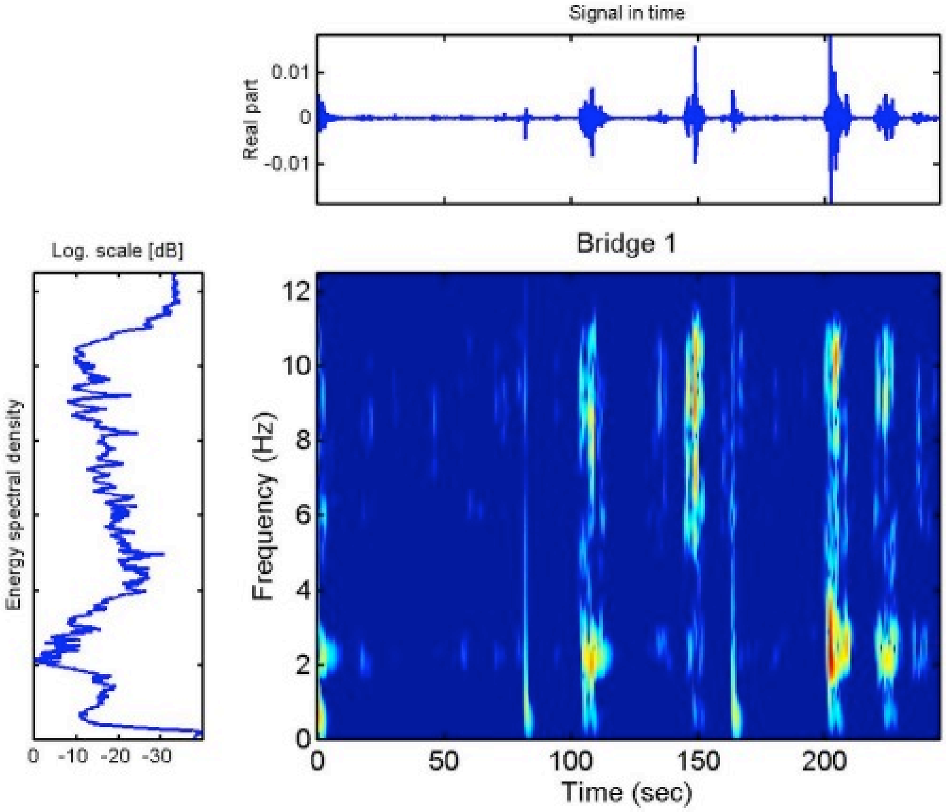

Figure 2: Time-frequency plots of seismic tracks recorded on top of bridge B1 (three 80 s records are attached). During the first 80 s data chunk no truck was crossing (only occasional cars), while two big trucks were crossing during the second and third 80 s chuncks.

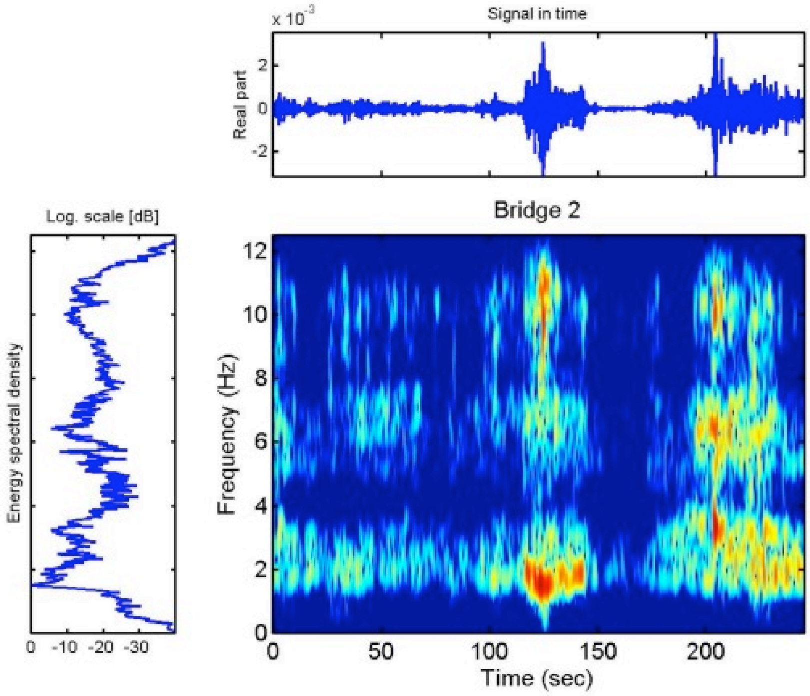

Figure 3: Seismic tracks recorded on top of bridge B2 (three 80 s records: no trucks, 1 truck, 1 truck).

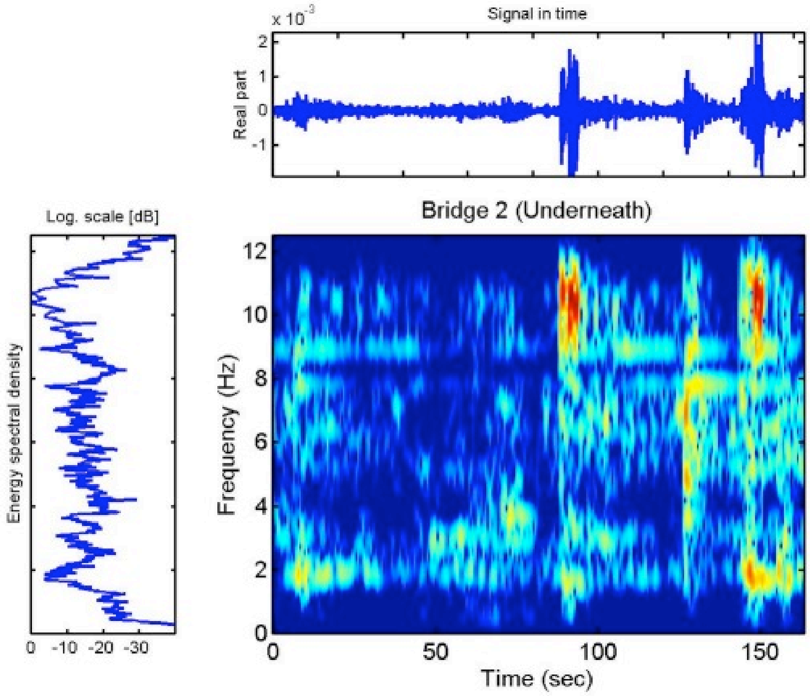

Figure 4: Seismic tracks recorded underneath bridge B2 (two 80 s records, no trucks, 3 trucks).

3 Coincidence measurements

Unfortunately Virgo DAQ system was not working at the time of the previous measurements, and so simultaneous Virgo seismometers recordings were lost. Therefore we carried out a second set of measurements with the aim of investigating the correlation between signals recorded at the bridges and simultaneously at Virgo by the on-line seismometers (episensors [2]). The main limitations for this measurement were (i) the poor ONO SOKKI memory capability (=16384 data points) which allowed for a max. lenght of one continous recording of 256 s at 64 Hz sampling frequency, or 640 s at 25.6 Hz; (ii) the short (approx. 1h) life of ONO SOKKI portable power supply; (iii) since our instrument was not endowed with its own GPS antenna, we had to adopt a very rough method to measure time, that is we used a digital wristwatch which at first we syncronized with the time displayed on the GPS board (in crate C11 Master Timing).

Two seismic records were taken at bridges B1 and B2 sites (figure 1). Details are given in table 1. For each measurement the start time (t_0) is the time when the seismometer signal cable was connected on the ono-sokki front panel. This event is easy to identify because it corresponds to when recorded data become different from zero (see figure 5). Figures 5 shows the time-frequency plots of both seismic recordings at the fi-pi-li bridge and compares it with the simultaneous recordings of the Virgo seismometer (episensor in Central building, 50 Hz data). Although signals appear different in the full frequency band, they do show similarities at low frequencies (1-4 Hz), see figure 6.

Sensor location	*Start time (GPS)*	*Record length (s)*	*Sampl. freq. (Hz)*
B1, on top	719834024	640	25.6
B1, on top	719834886	640	25.6
B1, on top	719835790	64	256
underneath B2, on basement	730894980	256	64
underneath B2, on basement	730895461	256	64

Table 1: Seismic measurements at bridges SS-206 (on Oct. 28, 2002) and Fi-Pi-Li (on March 5, 2003).

We computed the cross correlation between the 1-4 Hz filtered signals recorded at bridge B2 and simultaneously at the Virgo Central building by episensor 1 (near BS tower). Results are shown in figure 7. [1] We used the Matlab function *xcorr()* with option *'coeff'* which normalizes the correlation function by setting equal to 1 the auto-correlation maximum value (controllare). Both seismic recording show a significant correlation (commentare sulla significativita' della misura). The time lag of maximum correlation indicates that the episensor signals are delayed with respect to signals recorded at the bridge by $+5.4 \pm 1.0$ s and $+5.5 \pm 1.0$ s respectively (commento sulla scelta dell'errore). In figure 8 we show the 'syncronized signals' obtained by attaching the two 1-4 Hz filtered seismic records, in addition the two episensors signals are first syncronized by shifting them back by the measured delay. Also shown is the cross correlation between the syncronized signals.

Figure 9 shows the measurements performed at bridge B1 (SS-206 bridge). In this case we do not find evidence of any correlation between the seismic record at the bridge and the

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[1] Here we used the EW episensor component (ch #1), NS and vertical components give similar results, but a slightly poorer correlation.

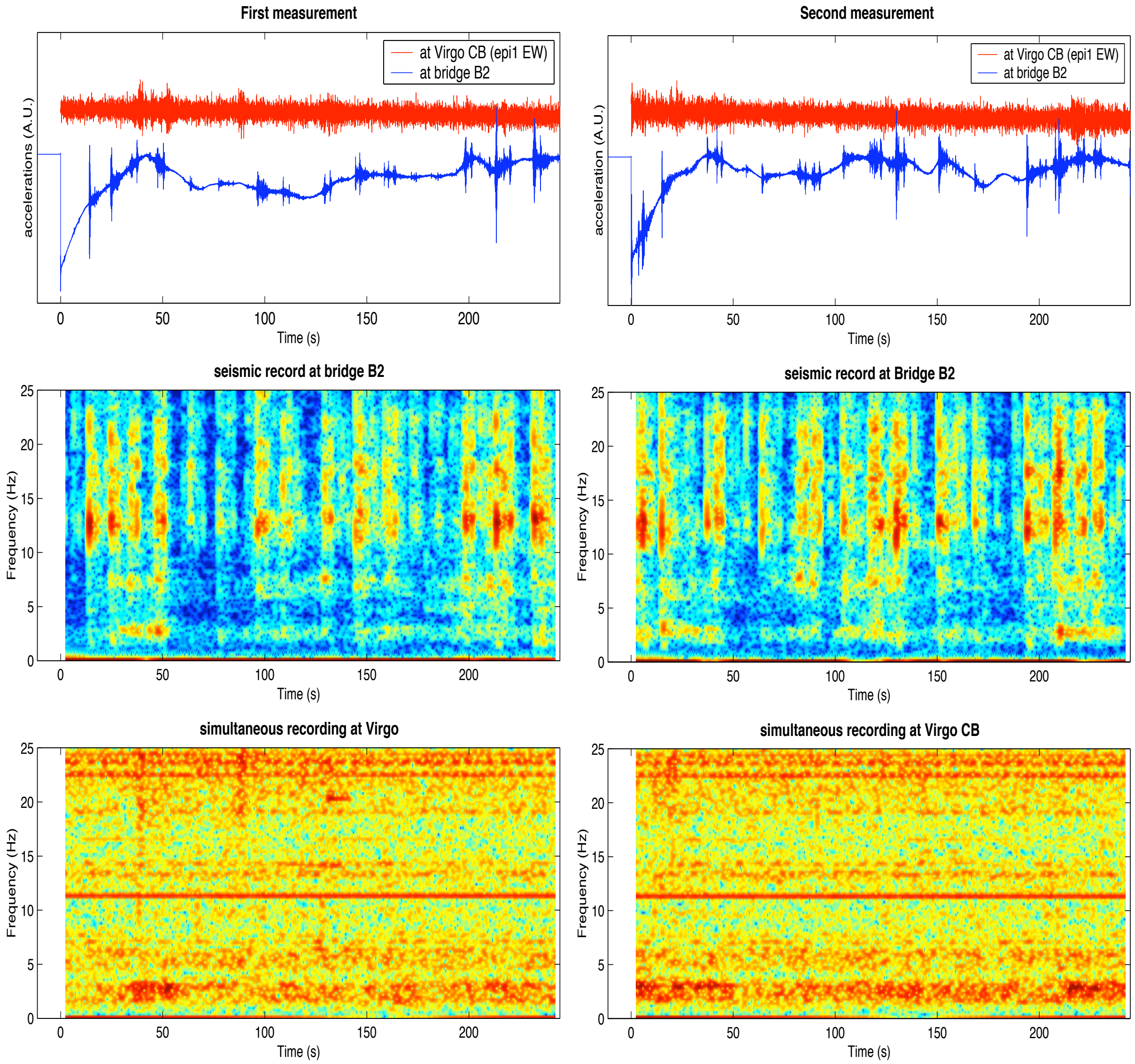

Figure 5: Top: simultaneous recordings at bridge B2 (fi-pi-li) (blue) and at Virgo CB (red). Middle: time-frequency plots of seismic tracks recorded at the bridge. Bottom: time-frequency plots of simultaneous tracks at Virgo CB (episensor 1, EW channel).

simultaneous seismic record at Virgo Central building. However it is reasonable that seismic bursts from bridge B1 are absorbed before reaching the Central building located ≈ 4 km far (in fact seismic attenuation is enhanced in soft soils such is the soil at Virgo, see Section 5). Would be likely instead that something is heard at the West terminal building located ≈ 2 km far from B1. Unfortunately at the time of this measurement the episensor seismometers in the terminal buildings had not been installed yet.

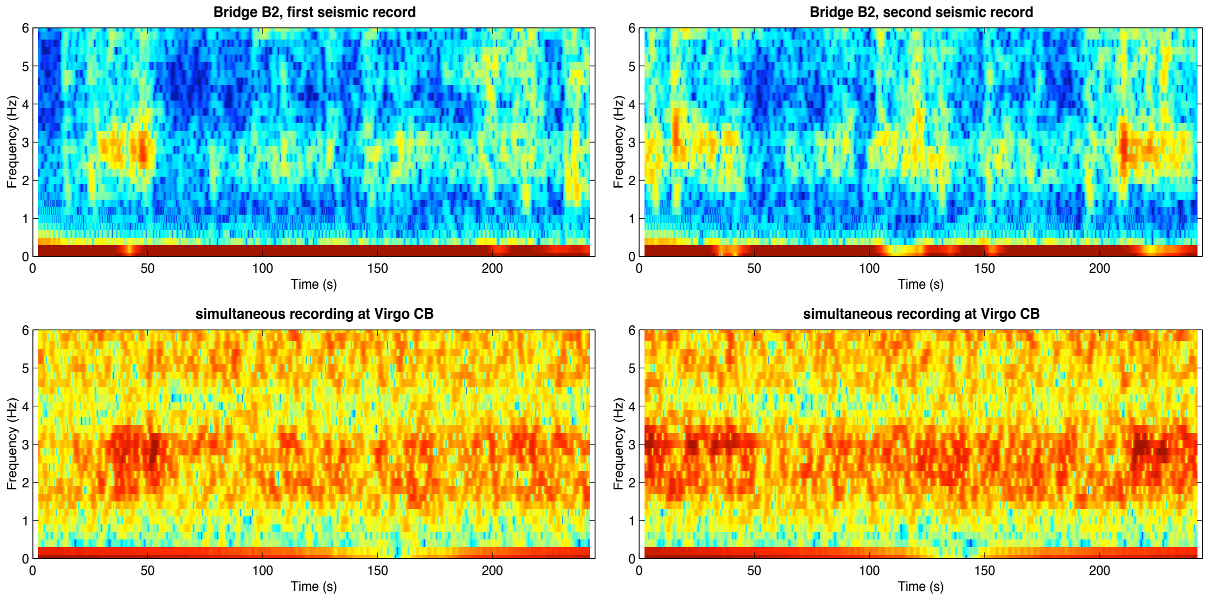

Figure 6: 1-6 Hz zoom of time-frequency plots in figure 5.

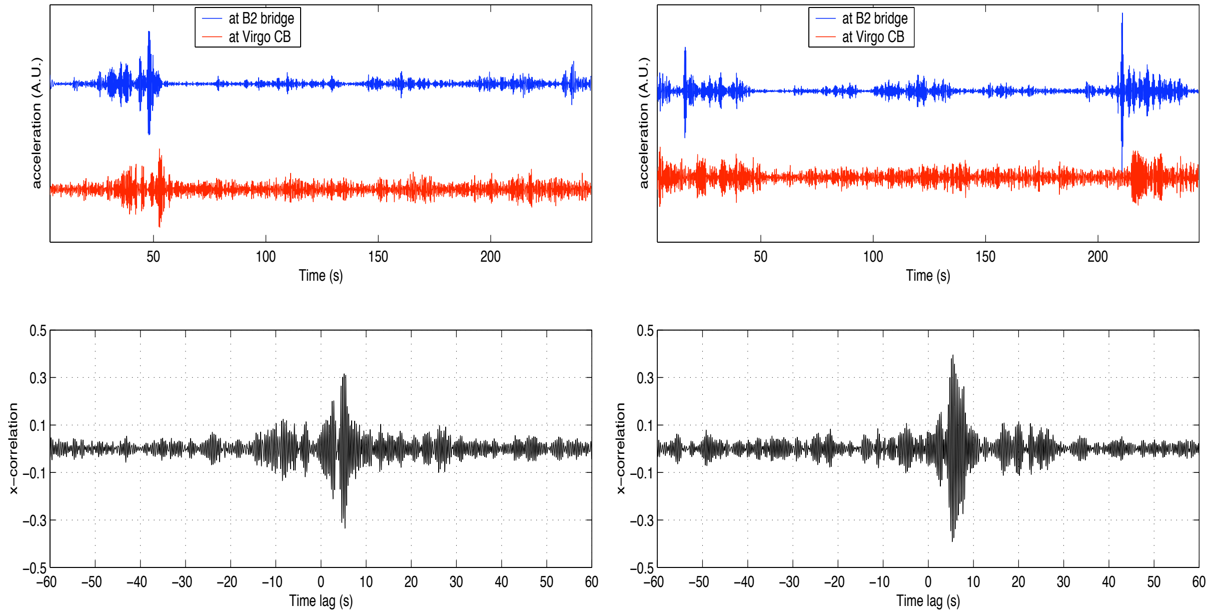

Figure 7: Top: same signals of figure 5 band-pass filtered between 1 and 4 Hz. Bottom: cross correlation of above signals with ±60 s time lags over the whole record lengh (≈ 256 s) (ono-sokki data were first resampled from 64 to 50 Hz using Matlab function *resample*()).

4 1-4 Hz seismic activity at terminal towers

Since May 2003 we have episensor seismometers installed and active inside the Virgo terminal buildings: channels Em_SEBDNE01,02,03 (North terminal building, respectively EW, NE and vertical axes) and channels Em_SEBDWE01,02,03 (West terminal building).

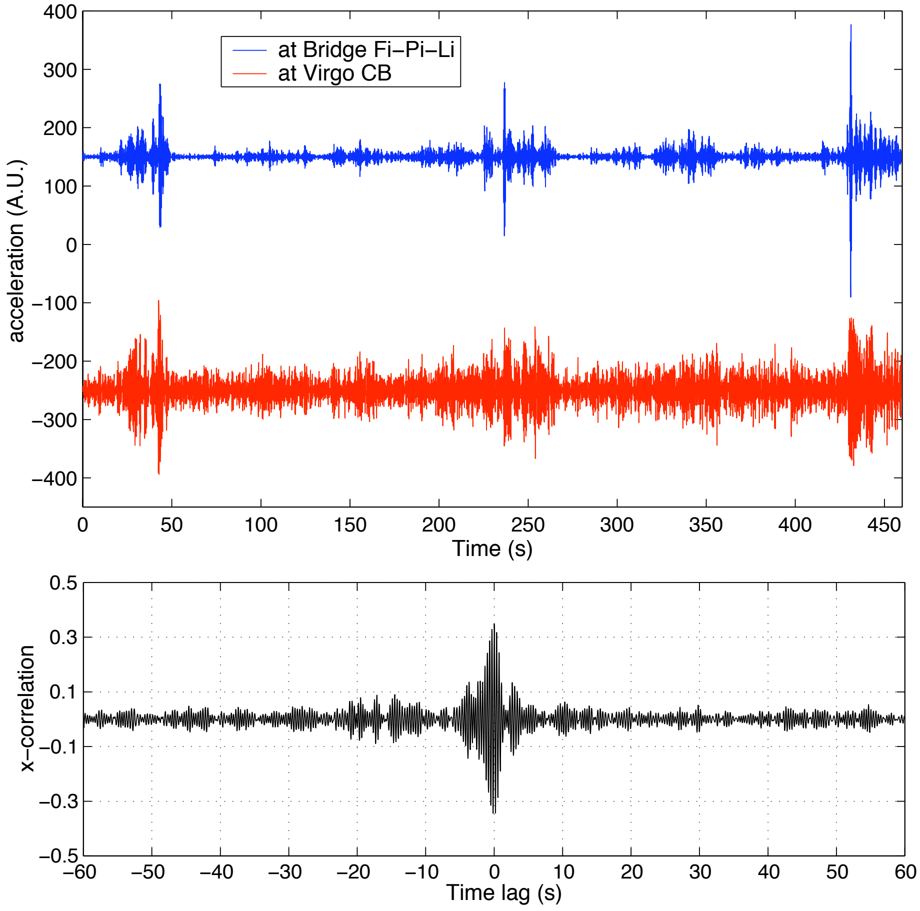

Figure 8: Top: signals of figure 7 are attached, episensor records are first shifted back by the measured delay. Bottom: cross correlation of signals above.

Figure 10 shows 1800 s simultaneous recordings of the low-frequency seismic activity at the Central, West and North terminal buildings. Seismic bursts of similar characteristics but less intense are present also at the North building, while the West building is quiter. There is no evidence of correlation among the signals (figure 11). It is in fact not likely that bursts from bridge B2 can be detected at the North building approximately 3 km far. Instead, it is reasonable that seismic bursts detected at the North building are originated at bridge B3 which is ≈ 1.5 km away (see map). Bridge B3 is similar in size and structure to B2, but no measurement has been performed at this bridge yet.

5 Properties of Virgo soil

Measurements above show evidence that seismic bursts at ≈ 2 Hz originated at bridge fi-pi-li are detected at Virgo Central building (BS tower, distance $= 1.5 \pm 0.2$ km) with a delay $+5.4 \pm 0.7$ s (average of two measurements).

Using these numbers we can derive a rough estimate of the velocity of propagation of the associated seismic wave.

$$v = (280 - 430) \pm 100 \text{ m/s}. \tag{1}$$

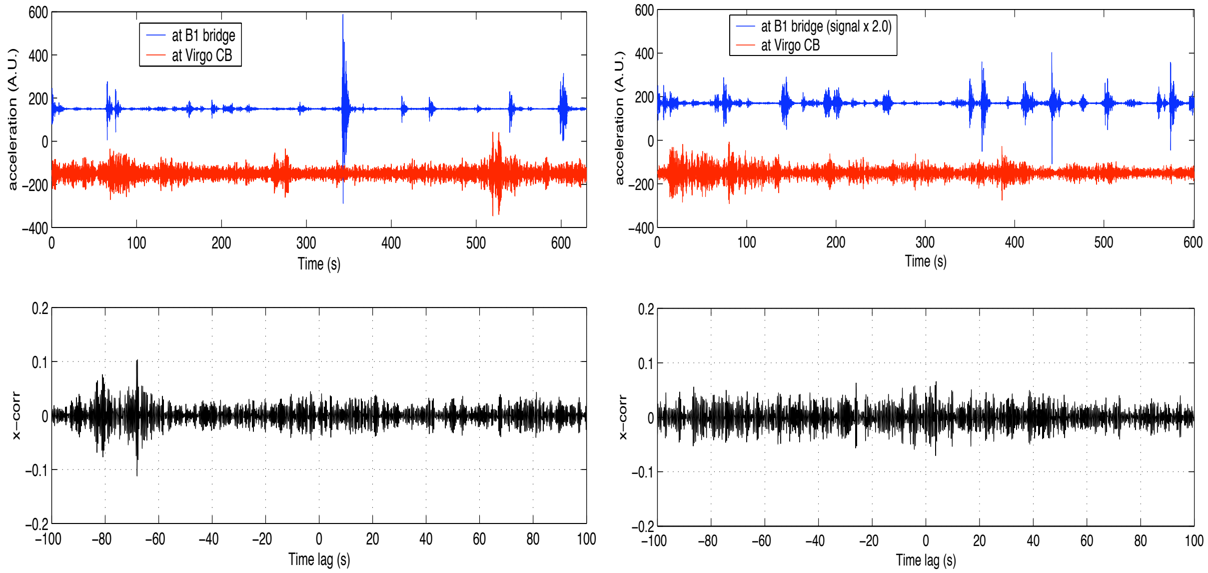

Figure 9: Top: recordings at bridge B1 (SS-206) and simultaneous recordings at Virgo CB by episensor 1, signals have been band-pass filtered between 1 and 4 Hz. Bottom: cross correlation of above signals with ±100 s time lags over the whole records length (≈ 640 s).

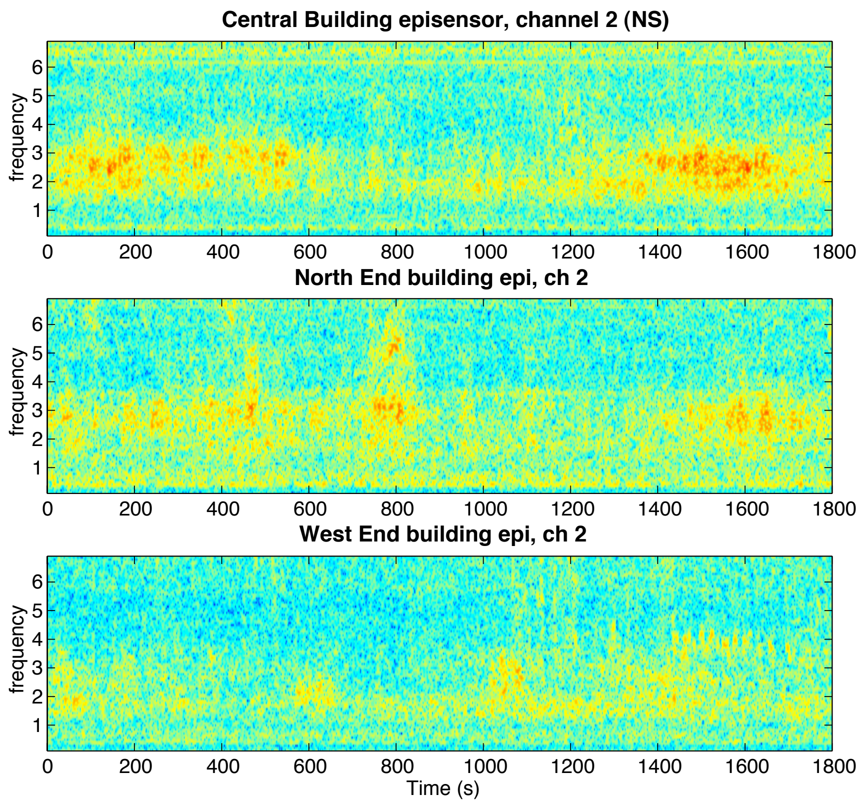

Figure 10: Time-freq. plot of simultaneous seismic recordings at the Virgo terminal buildings.

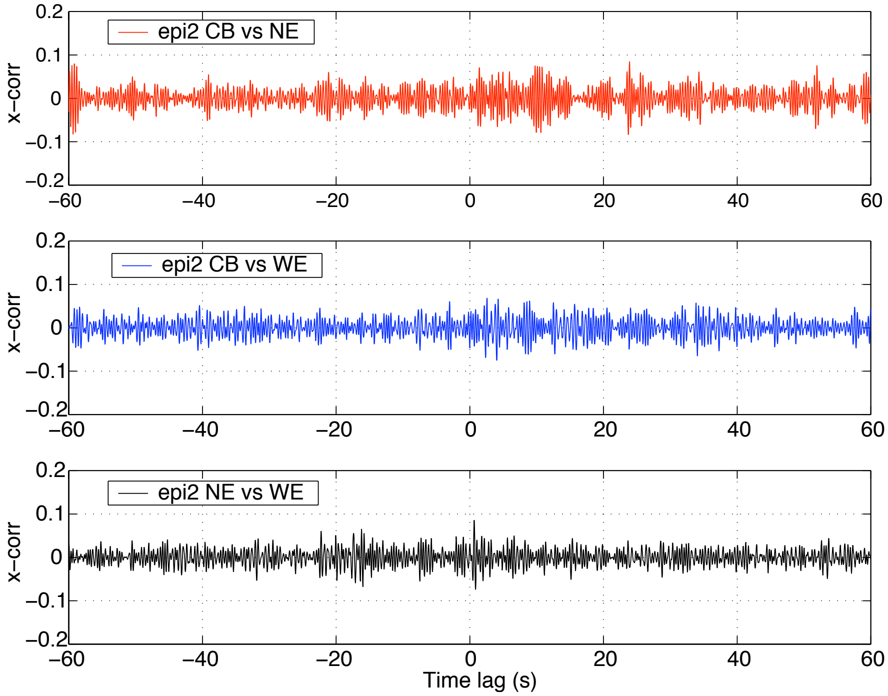

Figure 11: Cross correlations between signals in figure 10, only first 500 s are used to allow a comparison with figure 7.

The upper value is computed assuming +1s error in the wristwatch syncronization and an additional +1s error in measuring the time of cable insertion which give a shorter travel time of 3.4 ± 0.7 s. The statistical error is conservatively calculated using this shorter travel time. [2] This range of velocities is consistent with the propagation velocity of the surface seismic wave-field from the sea measured at Virgo in note [4]. This slow velocity value is typical of the near-surface propagation of seismic waves in soft soils [5] such as the recent marine sediments (lime and sand) of Virgo site.

Our measurements also show that at a distance ≈ 1.5 km only the low freq. component (≈ 2 Hz) of seismic bursts produced at bridges survives, while higher frequency compoenents (such as the ≈ 10 Hz component) are attenuated below the seismic noise floor.

We can use the seismic excitation from the fi-pi-li bridge to derive a rough estimate (upper limit) of the attenuation properties of the soil at Virgo site. We use the following parametrization for the attenuation of surface seismic waves [3]:

$$A(s,\omega) = \frac{A_0}{\sqrt{s}}\, exp(-\frac{\omega s}{2vQ}) \qquad (2)$$

where Q is the soil quality factor (also known as *Knopoff factor*: $1/Q = -\Delta E/2\pi E$, it measures the fraction of energy lost per oscillation period), s is the travelled distance, v, A and ω are the wave velocity, displacement amplitude and angular frequency respectively. We use $s = 1500$ m and $v = 400$ m/s (i.e. we neglect dispersion effects). We assume that the 2 Hz and 10 Hz components are produced with equal intensity at the fi-pi-li bridge (figures 3, 4 and 5), and for

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[2] A more accurate calculation should account for the fact that the error on wristwatch sync. is common to both measurements, while the error on cable insertion is uncorrelated, this would go in the direction of slightly reduceing the v upper value.

the amplitudes ratio we use: $A(2\ Hz)/A(10\ Hz) > 10$ which is the ratio of the RMS seismic displacements measured by the central building episensor in the frequency band (ref. figure 10 in note [1]) 1-4 Hz when bursts are present ($\approx 0.1\ \mu$m) and seismic noise floor in the frequency band 4-10 Hz ($\approx 0.01\ \mu$m). We derive: $Q < 40$. This low value of Q is in fact typical of soft soils (web site giapponese, give tipical values, table for different kind of soils). [3]

Using our extimates for Q (=40) and v (=400 m/s), we can compute the attenuation length (l = distance at which the wave amplitude is reduced by e) for 2 Hz, 6 Hz and 10 Hz seismic waves in Virgo soil using the above formula. We get: $l(2\ Hz) \simeq 2500$ m, $l(6\ Hz) \simeq 850$ m, $l(10\ Hz) \simeq 500$ m.

6 Conclusions and outlooks

Our measurements of oscillation of bridges nearby the Virgo site provide evidence for the hypothesis made in note [1] that observed seismic bursts at ≈ 2 Hz at Virgo central building are produced at bridge B2 when excited by heavy trucks.

Seismic noise at ≈ 2 Hz should not have any effect on the interferometer (such measurement was performed on the CITF, see note [2]). Instead it could be interesting as a candidate source of Newtonian noise. On the other hand, these seismic bursts are interesting because they can provide information on the properties of the soil at Virgo site (useful for Newtonian Noise studies which require soil modelling).

A more accurate measurements of bridges seismic bursts is actually now (Jan. 2004) in preparation. It consists of a seismic array of the type described in note [4] but with shorter spacing (≈ 100 m). It should hopefully confirm our results and provide a more precise meas. of velocity and direction of propagation, and soil properties.

References

[1] L. Holloway and I.Fiori *Seismic motion at Virgo* VIR-NOT-FIR-1390-246.

[2] I. Ferrante et al. *A first look to seismic data: seismic channels and the aliasing problem*, VIR-NOT-PIS-1390-184.

[3] O. Faggioni, F. Graziano *Elementi di sismologia* 2001 Ed. ETS Pisa.

[4] E. Marchetti, M. Mazzoni and M. Ripepe *Low frequency seismic wave-field array analysis at Virgo* VIR-NOT-FIR-1390-220.

[5] Odum K J et al. 2003 *USGS Open-file Report* 03-043 *(http://pubs.usgs.gov/of/2003/ofr-03-043/)*

[6] I. Ferrante *Seismic contribution to dark fringe signal during E3* VIR-NOT-PIS-1390-226.

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[3] In our estimate of Q we have also assumed that both the episensor and the piezotronics accelerometers have flat response in the range 2-12 Hz.