Monitoring Virgo anthropic seismic noise with seismometer arrays

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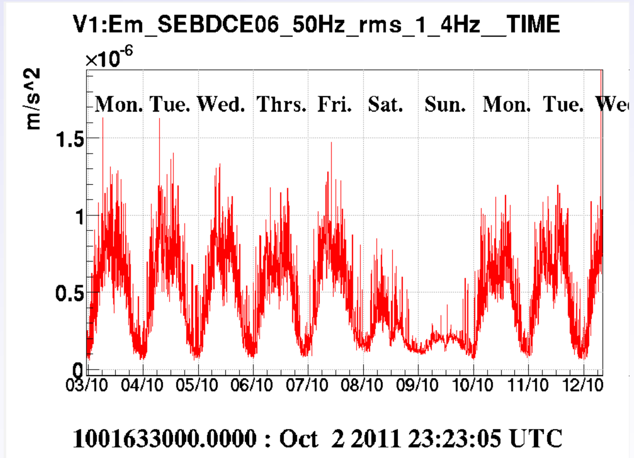
Introduction

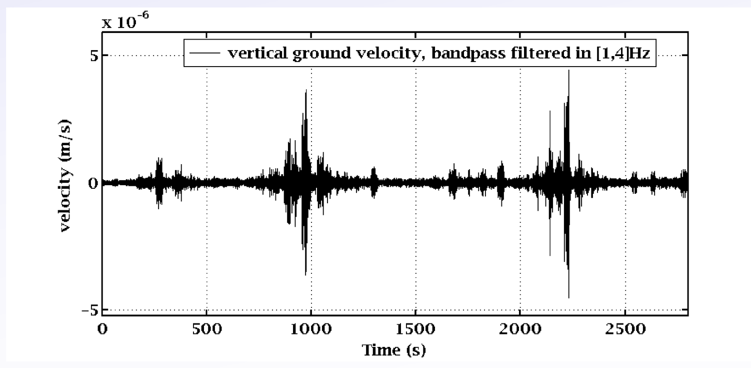
- Low frequency vibration of ground can couple noise to the interferometer output by means of diffused light or as local gravity gradient fluctuations. Characterization of intense low frequency sources in the ITF surroundings is the first step for improving noise monitoring eventually allowing implementation of noise subtraction techniques.
- While the below-1Hz seism at Virgo is better known and mainly associated to sea activity, less has been so far reported about the origin of 1-5Hz seism. We find seismic noise in this region is dominated by human activities in the vicinity of the Virgo site (few-km-range).
- In this poster, we report how the data of a small array of seismometers can be used to measure the velocity vector of low frequency surface waves at the Virgo site, and eventually identify some major ground seism sources in the 1-5Hz range.

Experimental buildings vibration noise

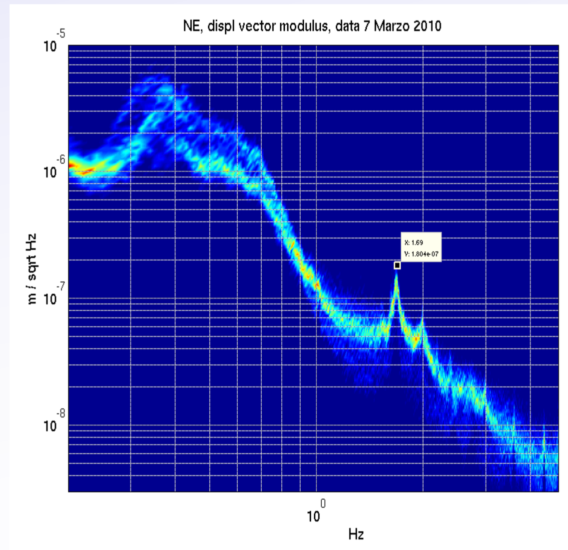
- The 1Hz to 5Hz RMS amplitude displays a marked working day modulation which denotes its antropic origin. In addition, a 2Hz component is correlated to wind activity.



Vertical seismometer, RMS in band 1Hz to 4Hz



Short time structure of 1Hz-5Hz Virgo ground seism. These bursts have been annoying during VSR4 (baffle noise)

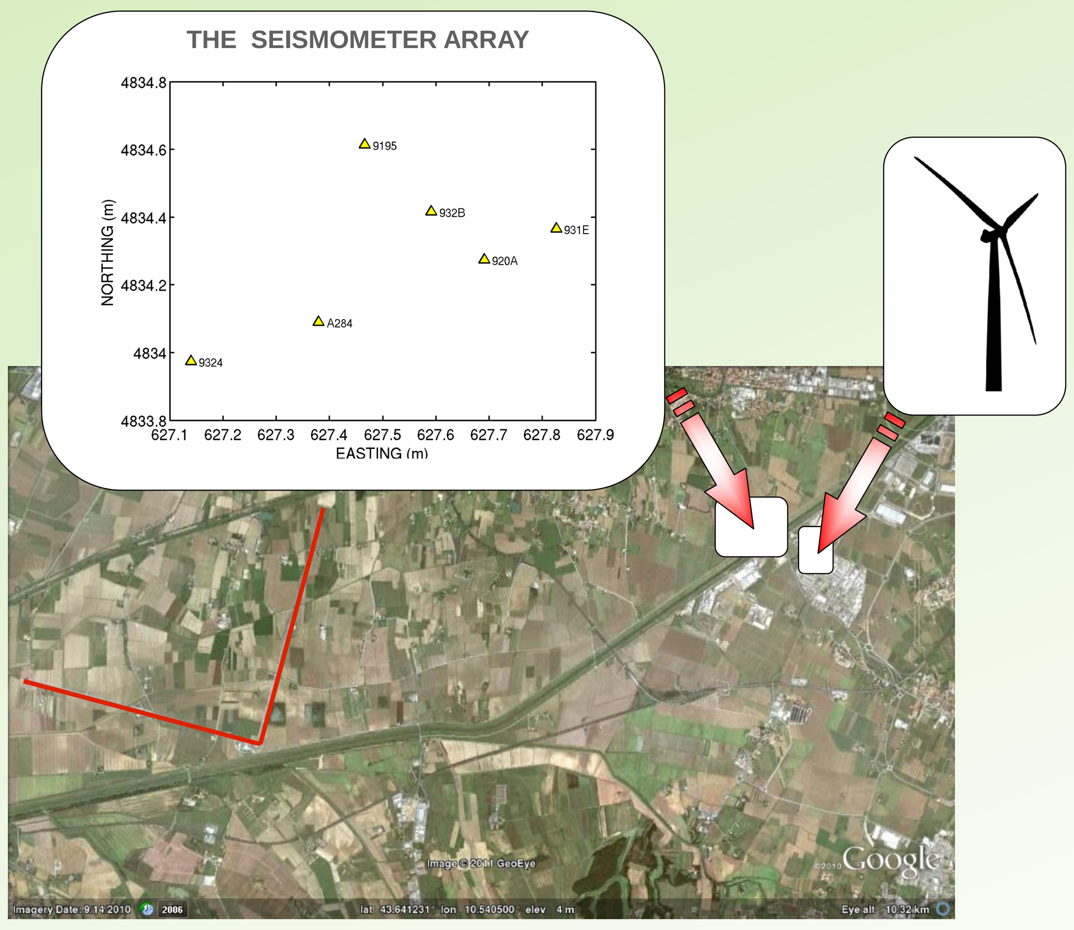


Displacement spectrum of NorthEnd building floor in a windy day

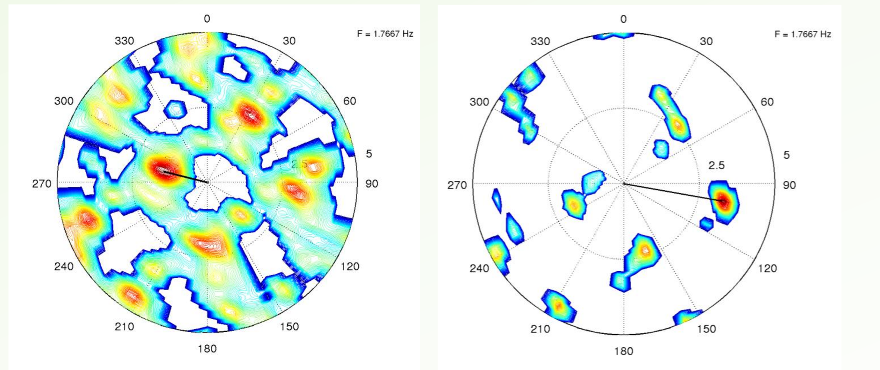
Wind turbines

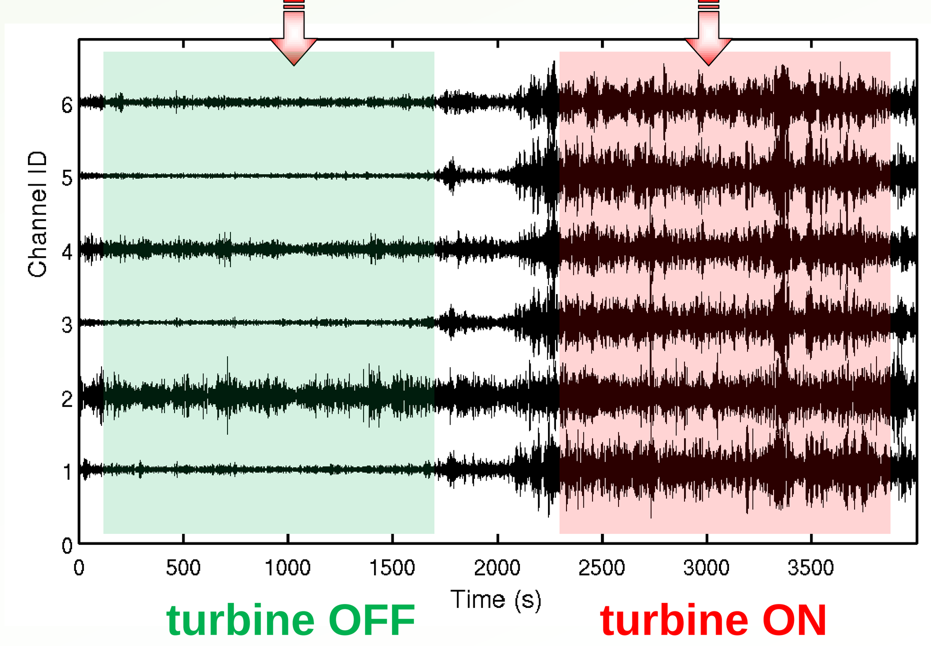
Some highlights from our study published in [G.Saccorotti et al, *Bull. of the Seismological Society of America v. 101 no. 2 p. 568-578, April 2011]:*

- Four 2MW wind turbines are located at 6km minimum distance from the Virgo site. These turbines are found to produce a persistent soil vibration at **1.7Hz** frequency (matching the tower's first flexural mode) which propagates large distance with little attenuation. The vibration becomes significantly larger when turbines rotate faster than 15 rpm, that is when wind speed at the hub height (100m from ground) is ≥ 8 m/s. In these conditions, a seismic signal is detected above quiet background noise at all Virgo buildings (6 to 12 km away). The small attenuation is explained assuming a double propagation path: half of vibrational energy propagates as surface shear wave, and half propagates (faster and less attenuated) along the deep carbonate rock layer.
- A six-seismometer array has been placed in the proximity of one turbine. Data are analyzed to extract the velocity module and direction of propagation (see insert). As the turbine switches on, it is evident the onset of a seismic wave propagating from the turbine direction and a speed of about 400m/s.



Velocity vector of the dominant seismic wave (BLACK line) impinging on the seismic array BEFORE, and AFTER the wind turbine switches on. NOTE: seismometers signal is band-pass filtered in a narrow band centered at 1.7Hz





"f-k analysis"

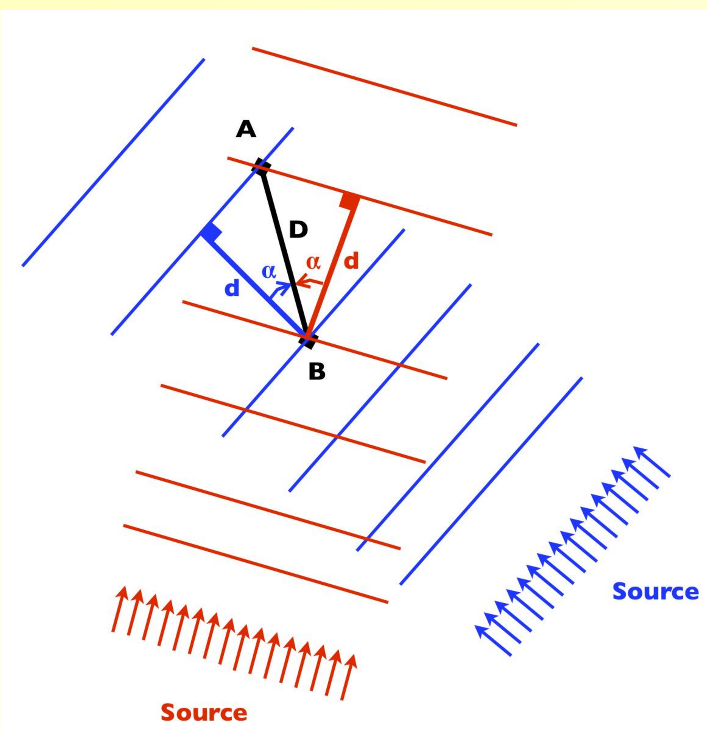
The "frequency-wavenumber array analysis" is well known to seismologists. It is conceptually the same technique adopted to reconstruct radar images. A hypothetical seismic source is assumed to produce plane wavefronts impinging on the detector array (i.e. assuming the source to be in the far field of the seismic sensors). A grid of possible direction and velocity module of the plane wavefront is assumed. Each grid cell is evaluated as a possible source's parameter values: all seismometer signals are rephased to account for the associated propagation delay, and the rephased signals are summed coherently. Then, the RMS of the summed signal is computed. The rephased signals would sum incoherently for any grid parameter cells except for that one matching the direction and velocity of an actual seismic source.

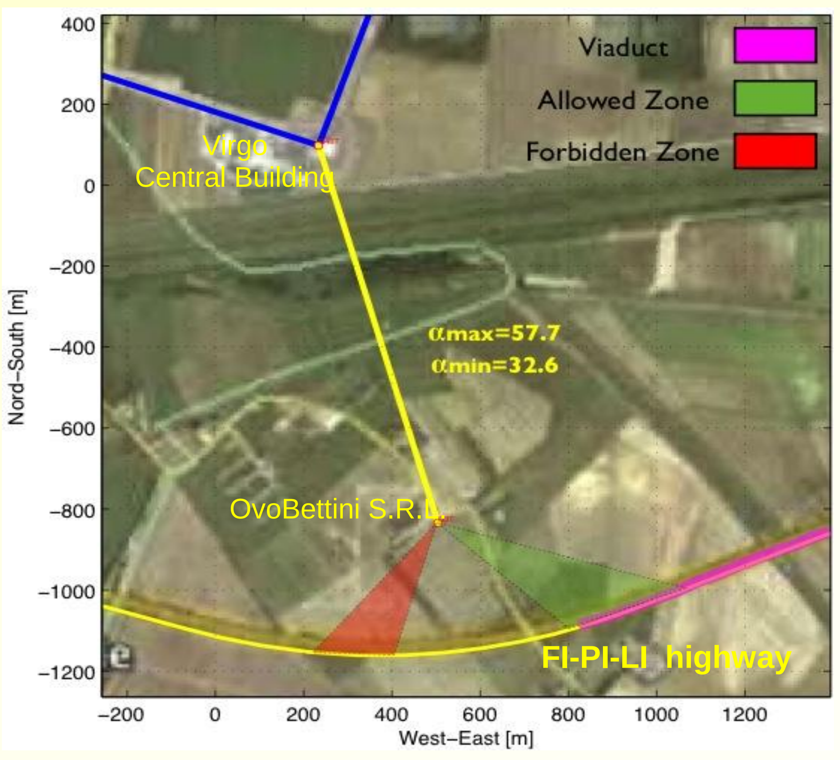
Highways

- When observed at short time scale, the daily modulated 1-5Hz ground vibration of Virgo buildings consists of random bursts, approx. 100s long.
- Our main suspect was the moderately traffic populated highways and roads around the Virgo site. In particular we suspect that seismic shocks are produced when heavy and fast vehicles (trucks) hit bumps in the paved road (at joints between viaduct sections).
- One such viaduct (about 500m long) is part of the FI-PI-LI highway and it is located about 1.5km South-SE of the Virgo central Building. We suspect trucks crossing this viaduct to being the source of the 1-5Hz seismic bursts detected at the Virgo central building. We briefly describe two measurement setup aimed to test this hypothesis.

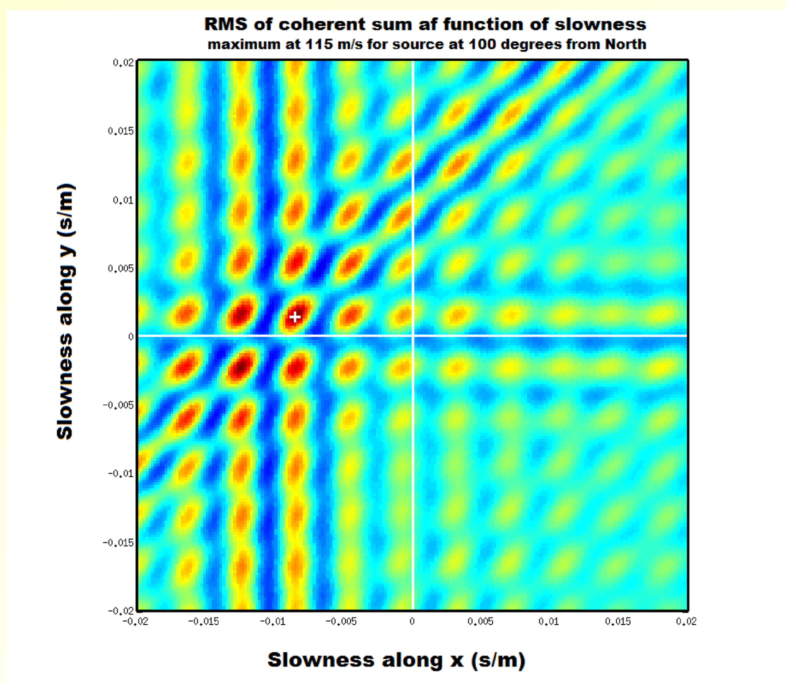
Two seismometer setup

- The setup consists of one permanent Virgo probe (Guralp 40T, indicated with "*A*") located inside the Virgo Central Building and one similar portable seismometer (indicated with "*B*") temporarily positioned approximately "half-way" (OvoBettini egg farm) between seismometer-*A* and the FI-PI-LI highway. Cleaned and synchronized records of the two seismometers were first band-pass filtered and then cross-correlated. Correlation is found for 0.1-1Hz filtered signals (sea microseism) at zero time lag, and for 1-5Hz filtered signals at time lag $\tau = (+1.9 \pm 0.2)$s. The "+" sign indicates that seismometer B signal anticipates A, as it should be for a South located source.
- Assuming a plane surface wave front from an hypothetical source impinging on the two seismometers, the wave direction (α) the velocity module (***v***) and the travel time (***τ***) of the wave front between the two seismometers are simply related: $\alpha = acos(\tau \cdot v/D)$, where *D=1060m* is the distance between the two seismometers. We assumed speed values in the range v=[325, 425] m/s (following measurements of surface wave speed in Virgo dry soil in *VIR-0281C-12*). The travel time is the measured correlation lag . We derived two possible intervals of wave directions: α = [33, 58]deg and $\alpha' = 2\pi - \alpha$. These angular sectors intercept the FI-PI-LI highway in two distinct segments. The east-most FI-PI-LI segment actually includes the suspected viaduct. Details in VIR-0303A-12.

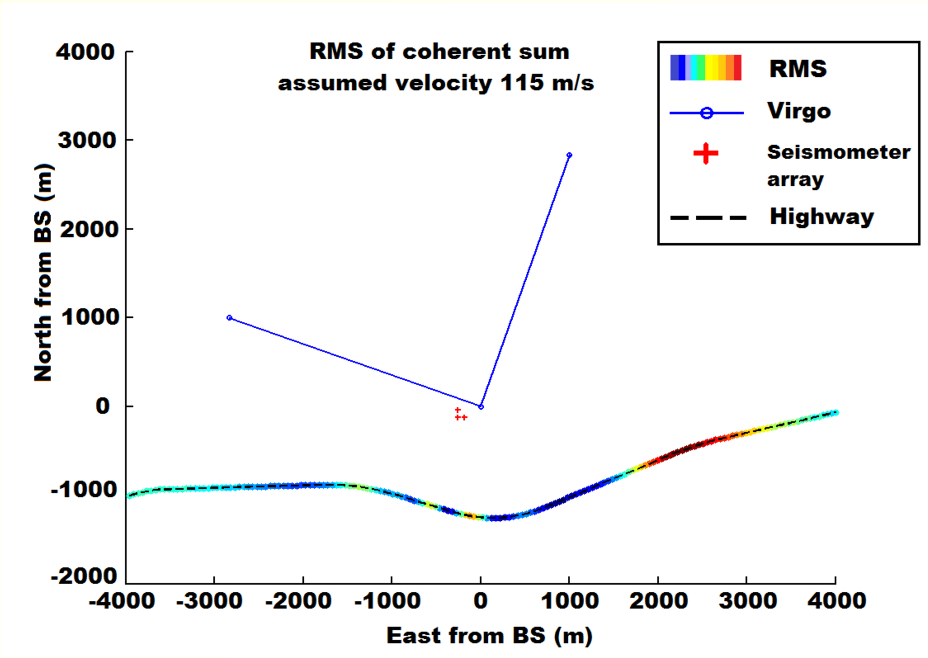




Three seismometer array near the central building



The signal of 3 seismometers were coherently summed as a function of assumed 'slowness' (inverse of velocity) on a rectangular grid. This allows for a search over both an unknown source direction and unknown wave propagation speed. This analysis is valid for sources located in the far-field, for which a plane wave can be assumed.



Same data, but RMS is calculated for a fixed velocity, and assuming that the source is located along the FI-PI-LI highway.
Both graphs were calculated using 100 second of data from vertical seismometers containing a typical seismic burst. The data was band-pass-filtered between 2 and 5 Hz. Note that other bursts can show different locations.

Outlooks

- Highway traffic and wind turbines essentially account for the 1-5Hz RMS ground seism of Virgo site during working hours or windy days. During VSR4, road traffic bursts were the probable triggers for noise visible in dark-fringe due to an un-damped freely swinging baffle. Thus, for AdV seems important that these and similar sources located a few km away from the Virgo site be kept under control.
- In first place, a good monitoring of this noise seems important for implementig data quality flags. This poster showed (only qualitatively) a powerful method for localizing the sources using a small array of seismometers. At least 3 portable seismometers are needed (but 4 or more would be better for redundancy and a better defined 'antenna pattern'). In second place, it seems important to watch close the evolution of project activities in the territory up to at least some km distance from the site. For example, EGO has been notified of projects of surface caves, one speedway, and additional wind turbines, proposed for installation at just a few km from the Virgo site.
- These and similar studies provide scientific arguments to support discussion with local authorities, for eventually limiting or moving futher away these noisy activities, or adopt even simple mitigation actions ... like fixing the most annoying road bumps.