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Underground earth strain and seismic radiation measurements with a laser interferometer and a dense small-aperture seismic array

Antonella Amoruso (1), **Luca Crescentini** (1), **Gaetano De Luca** (2), **Roberto Scarpa** (1), **Miguel Abril** (3) and **Alberto Cirella** (1)

(1) *Dipartimento di Fisica, Università dell'Aquila, Italy*

(2) *Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare, Assergi, L'Aquila, Italy*

(3) *Instituto Andaluz de Geofisica y Prevencion de Desastres Sismicos, Granada, Spain*

Abstract

This paper describes two geophysical instruments, installed in the underground physics laboratories of Gran Sasso (LNGS-INFN), located in the seismic zone of the Central Apennines, Italy. These instruments monitor strain and seismic radiation with very high sensitivity: one is a 90 m-long laser interferometer, sensitivity 3×10^{-12} ε, frequency response 10^{-7}-10^{2} Hz, and has been operating since 1994. The other is a small-aperture seismic array composed of 21 three-component short period (*Mark L4C-3D*) and 3 broadband (*Guralp CMG-3ESP*) seismometers. This dense array will be in operation at the beginning of 1998.

Key words *strain – seismic array – seismometry*

1. Introduction

The physics of earthquakes is based on the measurements of radiated seismic waves and ground displacements associated with these phenomena. Among the instruments developed by seismologists the inertial pendulum is not only the oldest, but also the most widespread device for measuring the main features of seismic waves. The advantages of this instrument are basically the simplicity of the theory, the high sensitivity, the robust design and the relative simple calibration methods, in spite of the quite reduced frequency band and linearity, which have been partially overcome by the introduction of electronic design such as the force balance method (see Wielandt, 1983).

Other instruments based on different physical principles, such as strainmeters and gyroscopes, are only partially used by seismologists (Benioff, 1935; Farrell, 1969; Aki and Richards, 1980).

Networks of short-period seismographs are by far the most widely used system for monitoring local and regional seismicity (Lee and Stewart, 1981). Broadband instruments constitute a powerful system to study details of seismic sources and are particularly used for the study of large earthquakes at global scale (Lay and Wallace, 1995). Moreover, arrays of seis-

Mailing address: Prof. Roberto Scarpa, Dipartimento di Fisica, Università dell'Aquila, 67010 Coppito, L'Aquila, Italy; e-mail: scarpa@aquila.infn.it

mographs and accelerometers are used to study details of sources and radiation patterns in the cases of earthquakes, nuclear underground explosions and volcanic activities (Bolt, 1976; Chouet, 1996).

Strainmeters and tiltmeters (see Agnew, 1986) are used to study the lower frequencies radiated from seismic sources and detect processes such as slow earthquakes and strain steps, *i.e.* anelastic deformations around seismic sources.

At present, the seismic activity of the Central Apennines and in particular the region of the Gran Sasso massif is relatively low compared to other seismically active areas of Europe, such as Central Greece.

We monitored three seismic swarms in August 1992, June 1994 and October 1996 with the largest earthquake having $M_L = 4.2$. These last two series of events have been also recorded by a linear accelerometric array, managed by SSN (Servizio Sismico Nazionale), located close to the Department of Physics (University of L'Aquila). These swarms constituted the largest events occurred since 1985 in the same region. This area, however, experienced destructive earthquakes in the past, and a M 7 earthquake occurred in 1703. Close to this region, the 1915 ($M_s = 6.8$) Avezzano earthquake occurred causing more than 15000 victims.

On the average, about 1 microearthquake per day above $M_L = 1$ within 20 km radius from LNGS-INFN (Laboratori Nazionali del Gran Sasso of Istituto Nazionale di Fisica Nucleare) occurs (see fig. 1). The facilities existing in these laboratories, other than the seismo-

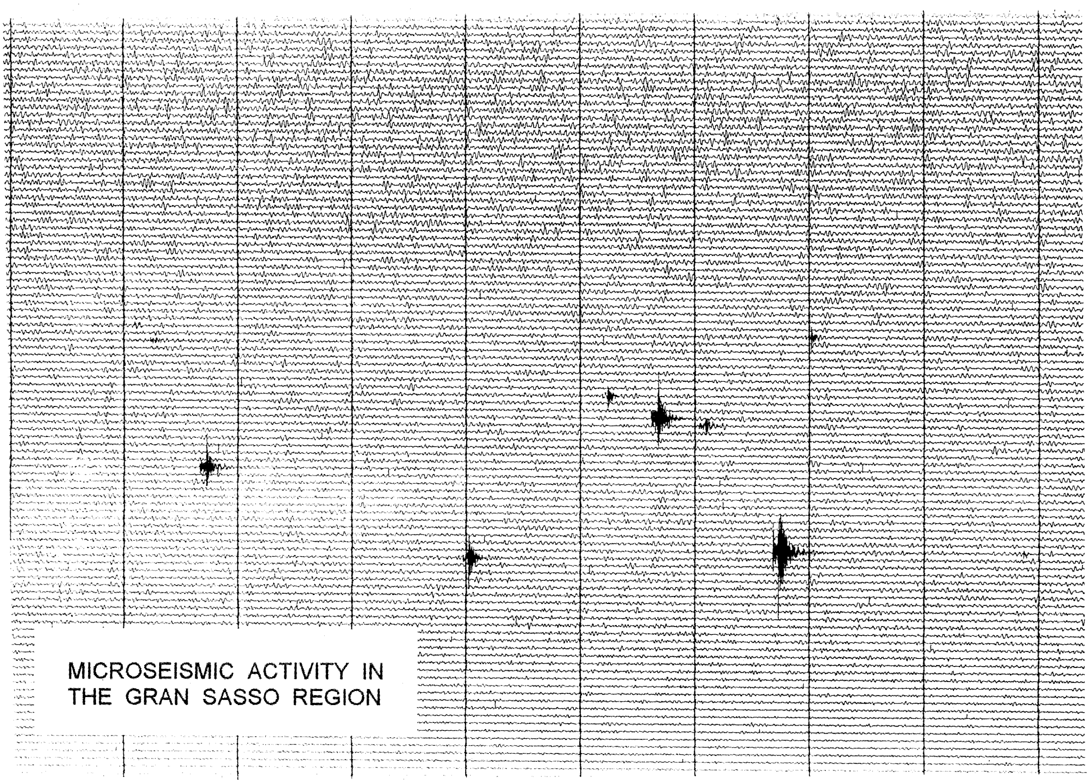


Fig. 1. Example of a drum record of microseismic activity at the end of February, 1992 in the Gran Sasso region.

tectonic features, make it an excellent site for studies related to the physics of earthquake source, the wave propagation in a complex medium and the development of high-sensitivity techniques for detection of earthquake precursors.

We describe in this paper two instruments which are designed to focus on two different aspects of seismic sources. The first is a very large-band instrument, a laser interferometer, developed to study earth strain very close to a fault segment. The second is a dense small-aperture seismic array (seismic antenna) specifically designed to study wave propagation phenomena and source processes of micro-earthquakes occurring in this region.

2. The underground laser interferometer

The underground laser interferometer (Crescentini and Renzella, 1991; Crescentini *et al.*, 1997) has been designed to measure the relative displacements of three monuments located at the vertices A, B and C of a right-angled triangle (see fig. 2), whose catheti cross a fault which is expected to have some modest level of activity (Calembert *et al.*, 1972).

The instrument is a Michelson interferometer, whose optical components are firmly linked to site rock. It is enclosed in a vacuum envelope decoupled from the end monuments and the optics by means of bellows. Pressure inside the envelope is dynamically maintained at 10^{-2} Pa. A temperature-controlled hut, maintained at 291 ± 0.1 K, was built around monument B. Room temperature in the tunnels is naturally fixed at about 280 ± 0.4 K. The output signal of the instrument is the voltage applied to a phase modulator, contained in one of the two arms of the interferometer, whose optical length is changed in order to maintain a fixed phase delay between the two interfering light beams.

To extend the dynamic range of the instrument, limited by the maximum voltage that can act on the phase modulator, a reset circuit was included, capable of changing the phase modulator optical length by $\pm \lambda$, each time the path-length difference $\Delta\lambda$ reaches $\mp \lambda/2$. Each output datum consists of two numbers: the voltage applied to the phase modulator sampled by a 12-bit A/D converter, and the number of resets since the acquisition started. Both the sequences of numbers are digitally filtered using a linear nonrecursive filter, decimated at 20 Hz, preanalyzed and recorded.

As a first step, from May 1994 to November 1995, the interferometer worked in an unequal-arm configuration, the measurement arm extending from B to C (see fig. 2). Since 1996 it has been working in an equal-arm configuration, the arm from B to A being used as reference.

The only difference in the two set-ups is that in the unequal-arm configuration the main vacuum chamber, which is situated in the B node, contains the beam-splitter, the phase modulator, and the retroreflector of the reference arm, while one of the two terminal chambers contains the retroreflector of the measuring arm. In the equal-arm configuration, the main chamber contains the beam-splitter and the phase modulator, while the terminal chambers contain the two retroreflectors.

The main characteristics of the instrument are: high sensitivity ($\Delta L/L \approx 10^{-12}$), fast sampling rate (up to 6 kHz), large dynamic range (unbounded in principle), the capability of following strain rates as high as 7×10^{-5} s^{-1}, and good reliability. The nominal resolution of the instrument is 3 $p\varepsilon$, although the actual capability of detecting geophysical signals is limited by the noise of the site, affected by atmospheric pressure fluctuations and by human activity. No changes in the noise spectral density have been evidenced as a consequence of the transformation of the instrument from the unequal-arm configuration to the equal-arm one.

A couple of weeks after the acquisition in the unequal-arm configuration started, on June 2, 1994, a swarm of local earthquakes occurred: the magnitude of the two largest events was between $M_L = 3$ and $M_L = 4$. Two extensional strain offsets were recorded on the interferometer during these same shocks, 4 $n\varepsilon$ and 16 $n\varepsilon$ in amplitude, respectively (Crescentini *et al.*, 1995). Their amplitudes were compatible with theoretical estimates by Dobrovol'skiy

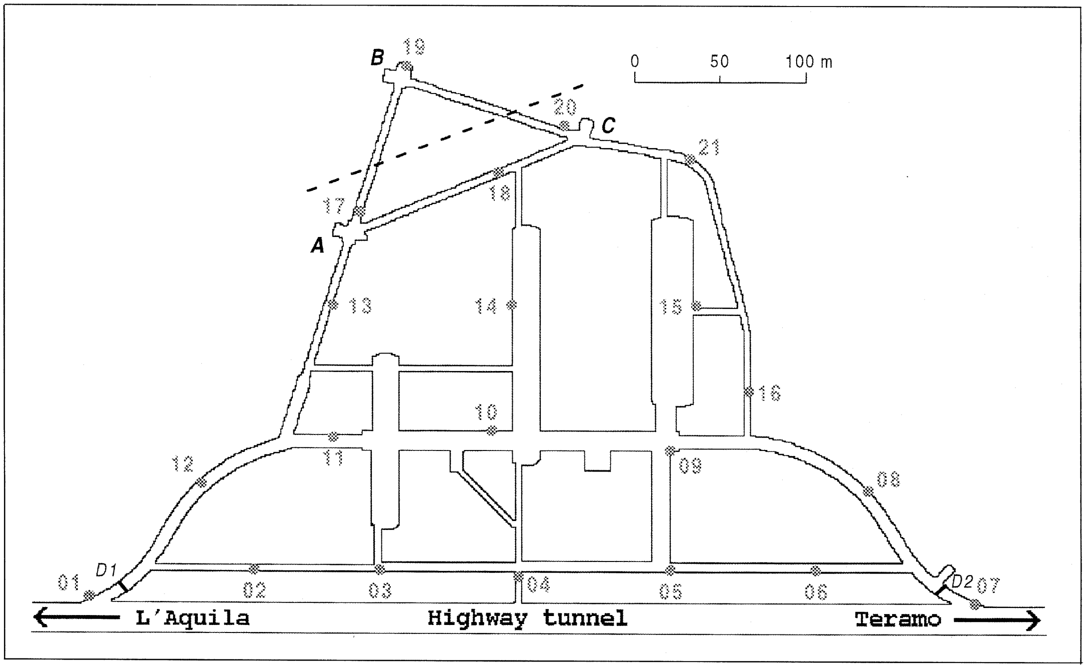


Fig. 2. Map of the underground laboratory (LNGS-INFN). End monuments of the interferometric strainmeter are located in A, B, and C. The dashed line roughly represents the fault crossed by the interferometer. Numbered closed dots represent the locations of the 21 three-components *Mark L4C-3D* of the dense seismic array.

(1992) for earthquakes having similar magnitude, depth, and epicentral distance. We have re-analysed the data, and a comparison between the theoretical earth tides and those retrived by experimental data evidenced an error in the sign of our deformation measurements from the beginning until June 21, 1994. Unfortunately, we corrected twice for the −1 factor due to the inverting differential amplifier (see Crescentini and Renzella, 1991); fig. 3 is the right picture. As a further consequence, no extensional strain transient occurred from the beginning of the operating time for about one month, but the recorded signal as a whole shows a monotonic compression, with periods of coarse stability. The interpretation of such a behavior in not simple, due to simultaneous effects of tectonics, relaxations of the tunnels which constitute the interferometric station and of the main halls of the underground laboratories.

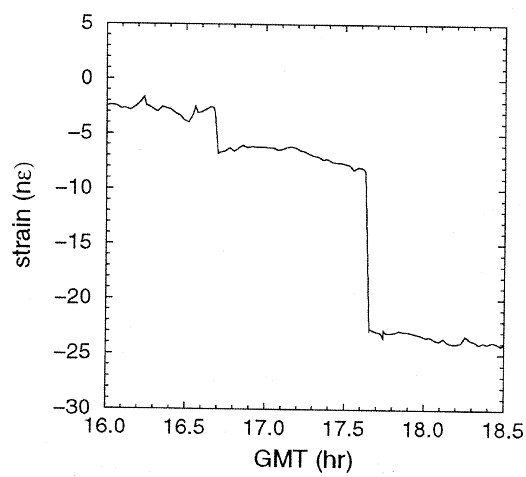


Fig. 3. Coseismic offsets recorded in coincidence with the two major events which occurred on June 2, 1994.

We also performed a few calculations, based on Okada's complete set of closed analytical expressions for the internal deformation fields due to shear and tensile faults in a half-space (Okada, 1992), in order to fit our coseismic data. We used the FPFIT solutions (Lee and Dodge, 1992) for the earthquakes by using the regional digital seismic network data. The expected coseismic strain offsets are consistent in sign but smaller in amplitude with respect to measured effects. However, coseismic effects could be enhanced through the tectonic discontinuity represented by the fault crossed by the interferometer, and the theoretical formulation gives strain without any correction (*i.e.*, local topography). Unfortunately, until summer 1994 high-frequency signals were filtered out during the acquisition process, and so it is impossible either to know the amplitude of the transitory seismic wave strain or to exclude spurious behaviors in the strainmeter.

We also tried to characterize our interferometer as a long-period seismometer. Figure 4 shows the signal recorded by the interferometer working in the equal-arm configuration during the transit of surface seismic waves produced by the M_s = 7.2 earthquake which occurred near Cyprus on October 9, 1996. The record shows good quality both in the region of maximum deformation and in the tails, where the peak-to-peak amplitude is lower than 10^{-9}. Figure 4 shows filtered data in different frequency ranges in order to evidence different seismic phases. In fact, even if seismic waves are differently attenuated depending on source site due to the directionality of the interferometer, all phases are recordable. A comparison of the site noise recorded by the interferometer and the typical ambient noise of the most similar seismic instruments, *i.e.*, the very-broadband horizontal seismometers of the MEDNET stations, is shown in fig. 5. For frequencies lower than 10^{-3} Hz, our noise level is lower than «quiet» MEDNET stations, *i.e.*, MDT MIDELT in Morocco (Mazza and Morelli, 1990). For frequencies in the range $10^{-3} \div 0.25$ Hz, our noise level is higher, probably due to pressure effects.

To avoid air entering from the highway tunnel, the underground LNGS-INFN laboratories

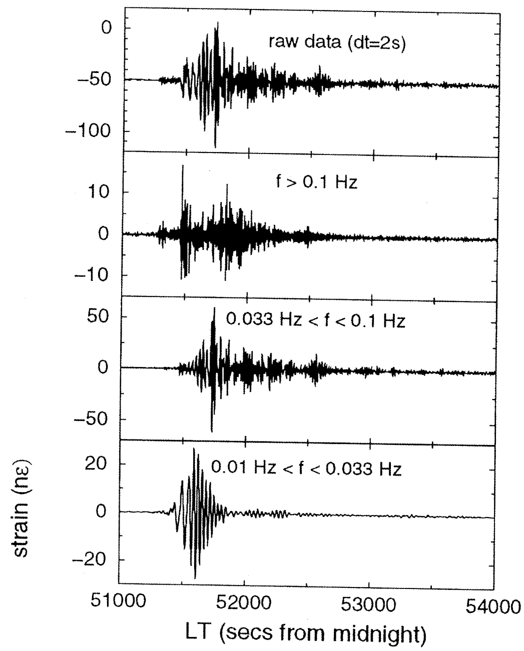


Fig. 4. Signal recorded during the transit of teleseismic waves produced by a M_s = 7.2 earthquake in Cyprus (October 9, 1996). Raw data and filtered data are shown (see text).

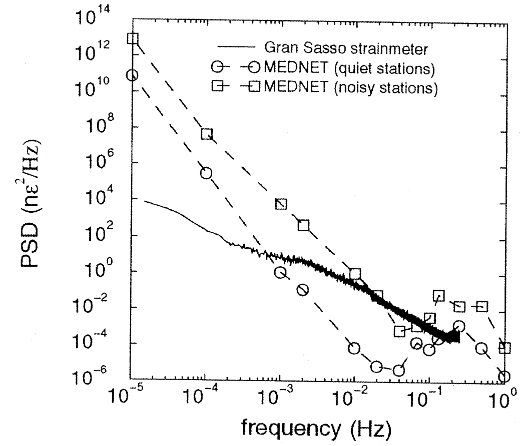


Fig. 5. Power spectral density: GS, present work; MEDNET (noisy stations), maximum noise of MEDNET horizontal seismometers; MEDNET (quiet stations), minimum noise of MEDNET horizontal seismometers.

are closed by two main doors (D1 and D2 in fig. 2), and a 50 Pa overpressure between inner and outer air is dynamically maintained. Consequently, inner air pressure is highly sensitive to traffic in the highway tunnel, and to openings of the main doors, thus causing a complex pressure pattern inside the laboratories, which is probably the origin of the noise excess evident in fig. 5. Up to now, we have monitored atmospheric pressure by means of a one capacitance manometer located in the hut surrounding the B monument, but more pressure transducers are going to be installed in different places in the tunnels. We hope that a better knowledge of the pressure pattern would allow a better removal of undesired effects.

As regards frequencies higher than 0.25 Hz, at present high-frequency records (10 Hz) are triggered by seismic events, and consequentely high-frequency records during quiet periods are not available, but in the near future we will continuously record at 10 Hz.

3. The underground small-aperture seismic array

A seismic array is a set of seismographs distributed over an area of the Earth's surface at spacing narrow enough so that the signal waveform may be correlated between adjacent seismometers (Aki and Richards, 1980). The

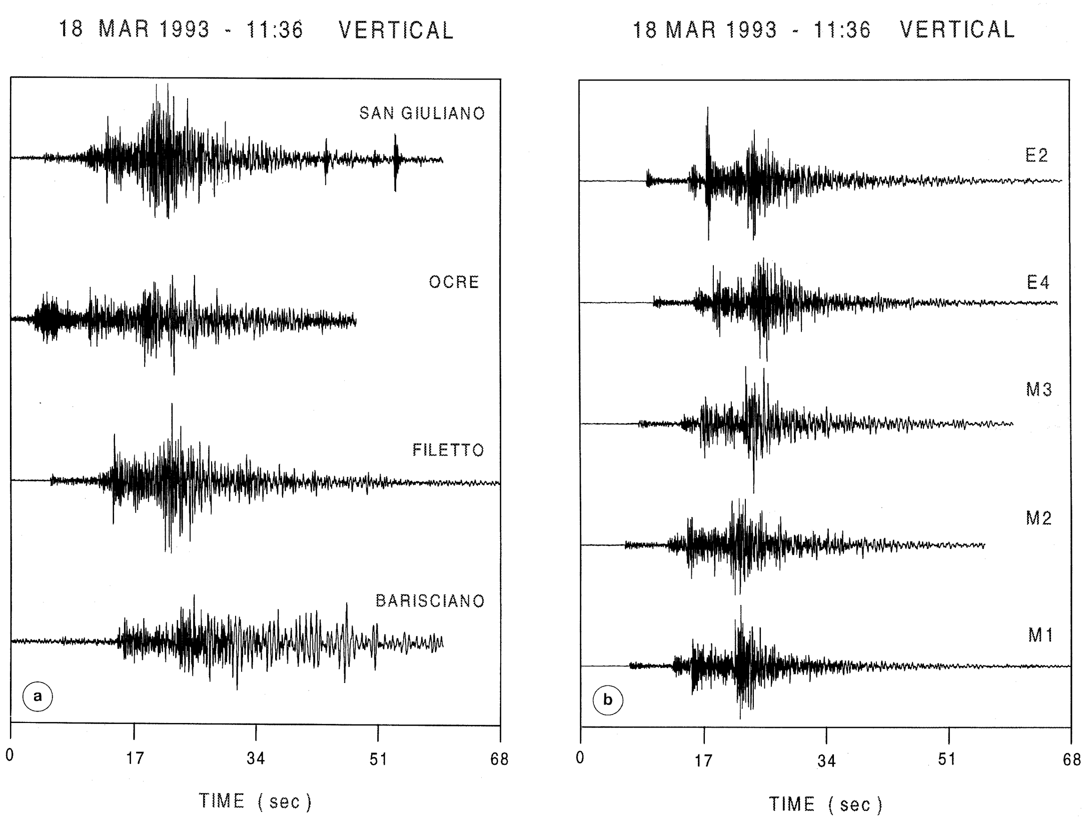


Fig. 6a,b. Examples of seismograms recorded by regional seismic network (a) and by underground L-shaped array (b).

main advantages of such geometrical configurations are an improvement in signal-to-noise ratio and the possibility to perform a detailed analysis of wave propagation and composition. The development of large-aperture seismic arrays such as LASA in Montana, USA (Green *et al.*, 1965) and NORSAR in Norway (Kedrov and Ovtchinnikov, 1990) led to many improvements in the knowledge of the Earth's structure (see, *e.g.*, Aki *et al.*, 1977) other than the possibility to monitor underground nuclear explosions.

More recent developments of these arrays make use of fewer sensors and a smaller aperture to reduce the effects of lateral inhomogeneities (Mykkeltveit, 1985). The use of very small arrays close to active volcanoes, with station spacing of a few tens of meters, is another promising method to understand the dynamics of seismic sources and the Earth's structure at a local scale (see Chouet *et al.*, 1997; De Luca *et al.*, 1997a; Milana *et al.*, 1996).

The need to monitor local seismicity in the very large underground physics laboratories of LNGS-INFN led to some preliminary experiments to understand the site response. We deployed, early in 1993, an L-shaped array along the access to the LNGS, having a spatial extension of 10.5 km. This array was formed by 17 three-component short-period digital seismic stations spaced 600 m (De Luca *et al.*, 1997b).

In the same region, around the valleys close to the laboratories, a digital seismic network has been installed currently equipped with 18 *Lennartz Mars-88* three-component short-period seismic stations. Figures 6a,b respectively show an example of seismograms recorded by the regional seismic network and by the underground L-shaped array.

Two important features of seismic response in the region have been observed: a substantial homogeneity of spectral response from underground linear array and, for *S* waves, an average decrease of amplitudes with respect to the data recorded at the surface, in the band 1-8 Hz. In particular, the horizontal components are reduced by a factor 4 while the vertical one is reduced by a factor 2 (see fig. 7).

Strain monitoring in the same region through GPS, EDM, levellings and microgravimetry is also carried out; moreover the regional digital three-component seismic network will be expanded to 20 instruments within 1997, making it one of the most dense modern devices working in seismically active areas of Europe.

The optimal array configuration is generally obtained through a compromise between the need to sample coherent portions of wavefield and the need for adequate azimuthal resolution, which requires a large antenna aperture. In the Gran Sasso tunnel we are, however, constrained by the limited distances and we decided to start with 21 receivers. In consequence, the underground seismic array has a

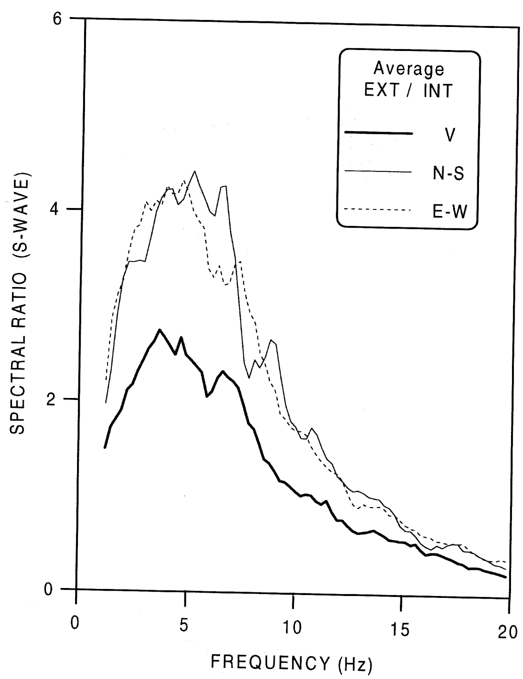


Fig. 7. Surface stations response for *S*-waves with respect to underground array. Log-average spectral ratios of 10 events within a distance range 40 km from LNGS-INFN are illustrated. The three curves and symbols refer to the vertical (bold line), north-south (thin line) and east-west (dashed line) components.

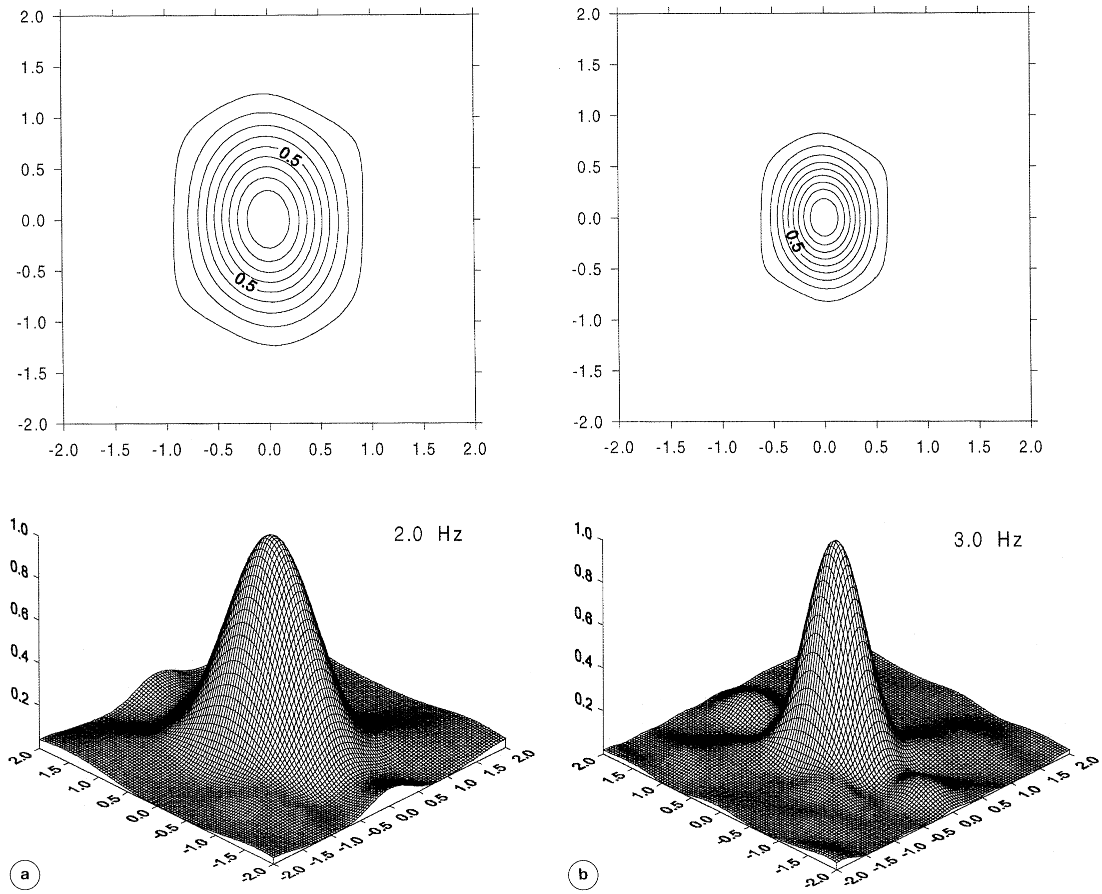


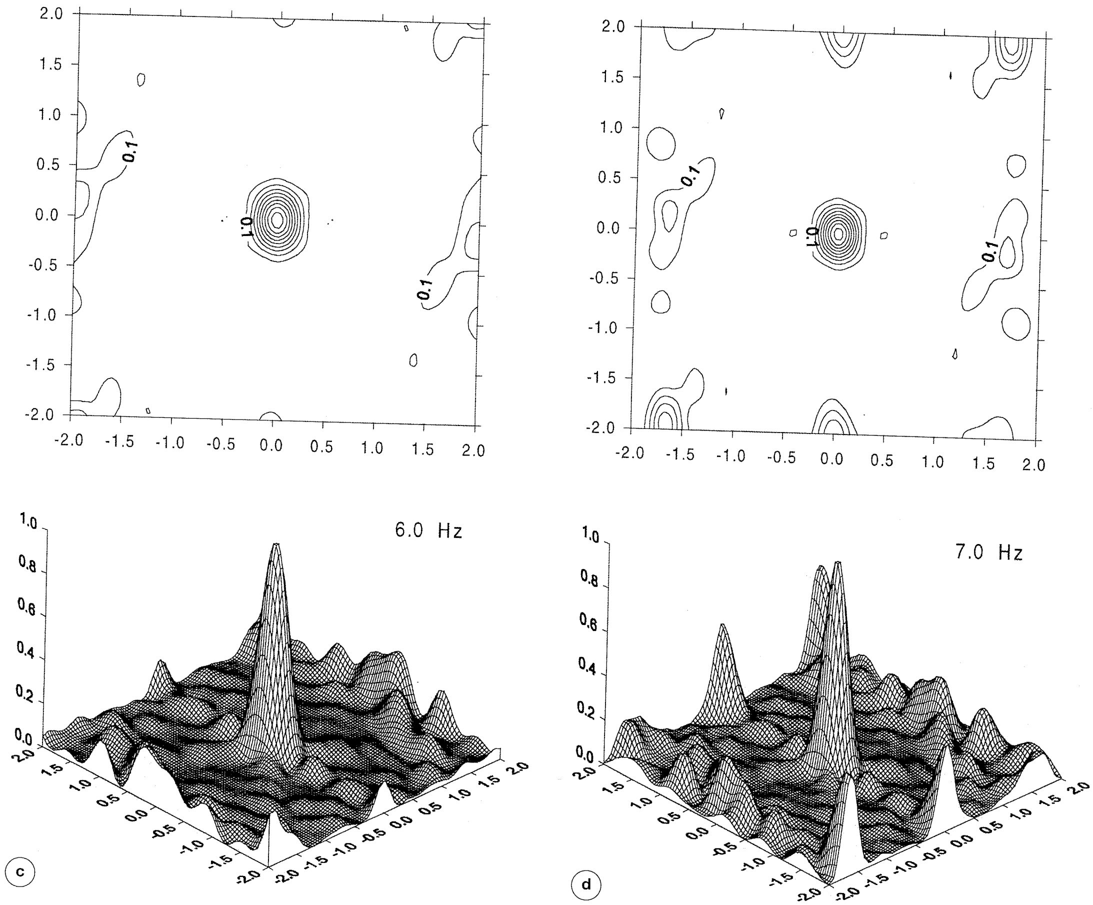
Fig. 8a-d. Slowness (s/km) power spectra calculated for the vertical component of motion of seismic array

small aperture (400 m × 600 m) and the average spacing between the short-period seismographs is about 90 m (fig. 2), thus allowing to resolve wavelengths in the range 180-500 m which correspond to phase velocity 0.2-10 km/s (the frequency response is in the range 1-20 Hz).

We used the analysis of slowness beam patterns produced by array impulse responses (Capon, 1969), showing a limited resolution at frequencies lower than 2 Hz and the presence of spatial aliasing at frequencies larger than 6-7 Hz (figs. 8a-d). This analysis, however, does not take into account the presence of three-component sensors which should improve phase resolution and detection of the array. Moreover the use of the MUSIC method (Schmidt, 1986) also contributes to improving the detection capabilities of this underground array which should be useful for resolving details of radiation in the typical frequency bands of microearthquakes and regional earthquakes.

The seismic array is under installation and is expected to be in operation at the beginning of 1998; three broadband seismographs will be added in the near future.

At present, we have developed the electronics and the data acquisition system, which con-



shown in fig. 2, at 2 Hz (a); 3 Hz (b); 6 Hz (c) and 7 Hz (d).

stitute an original project. In fact, this array has been designed to satisfy the following criteria:

a) Each transducer is equipped with a calibration and a shunt system. The critical damping (0.67) is reached with a 10 kΩ shunt resistance; a portable system to calibrate the sensors has also been devised.

b) The signals from the transducers are digitized by 24-bits A/D converters (21-bits at 200 Hz sampling rate) and then sent to PC-boards; moreover a few notebooks control all the channels, providing time syncronization and control functions.

c) A hub connects all the notebooks; RS485-RS232 interfaces are used among the elements of the array.

d) Two servers provide data acquisition, threshold criteria and real-time processing of seismic data.

e) A LAN is used for networking the data to other research centers in Europe or all over the world.

This dense array will form an unique, very highly sensitive antenna able to detect and identify the main parameters of regional seismicity.

A complementary project is the installation of a medium-range L-shaped array, having a maximum length of 7 km, in the tunnel that will be excavated for the independent access to the underground laboratories of LNGS-INFN. Unfortunately, the installation of this latter array cannot be scheduled since the excavation time cannot be predicted accurately.

4. Conclusions

Two advanced geophysical instruments have recently been developed in Central Italy, in the seismogenetic region of Gran Sasso. Both are located underground, allowing a sensitivity for instruments located in sesimic regions never gained before.

The interferometer is really a broadband instrument detecting earth strain at frequencies lower than 10^{-7} Hz and radiation from seismic sources with noise much lower than broadband seismic stations. The dense small-aperture seismic array is another powerful high-sensitivity instrument designed and currently under realization and installation.

The underground location beneath Gran Sasso has proved to be an ideal site, in spite of the local noise sources due to human activity, to record seismic waves from regional and local microearthquakes. Its location is unique in the world, due to the close distance from active fault segments of the seismogenetic zone of the Central Apennines.

The scientific objectives to this multichannel seismic observational system are an improvement in the seismotectonical knowledge of a high potential seismogenetic region of Italy and a very detailed study of the physical processes leading to seismic ruptures in the area. Moreover, the installation of the underground seismic arrays will allow an experimental study of wave propagation phenomena within a complex medium, leading to results of relevant interest for seismic hazard evaluation in areas of complex geology, for physics of earthquake process, with particular reference to the study of rupture preparation and for all relevant precursory phenomena, seismic radiation and earthquake waveform modeling for hazard reduction.

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