Seismic and volcanic risk evaluation by large area geo-monitoring optical fibre sensor networks: the SIMONA project

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Abstract

As demonstrated by many lectures, seismic and volcanic phenomena are strongly related to ground deformation and gaseous emissions. Thus to mitigate environmental risks, a continuous monitoring of ground strain and of the changes in the composition of gaseous emissions can be a very useful tool. The SIMONA (Environmental Integrated Monitoring System) Project aims at fixing, realizing and experimenting an innovative regional monitoring system, based on innovative optoelectronic devices, which is able to exceed the existing limits in order to increase sensibly the interpretation of geo-physical phenomena and the long term mitigation of seismic and volcanic hazards.
Keywords: optoelectronic devices, AOTF, FBG sensor, natural hazards prediction.

1 Introduction

Natural hazards risk evaluation has been one on the most investigated topics by scientific community in the last decades. Nevertheless seismic and volcanic events prevention and forecasting is still one of the major goals to guarantee the quality of life in high crowded areas.

Seismic and volcanic risk mitigation is essentially based on accurate processing monitoring, to follow and forecast their evolution. The most useful parameters to describe these evolutions of are strain changes (Chouet [1] and Ohminato etal. [2]), both static or quasi-static and dynamic. The former, in the band of 0.001-0.01 Hz, are related to permanent or long period deformation phenomena, as magma movements; the latter are related to ground movement directly linked to seismic waves.

Strain changes represent the most important effect related to the behavior of the rocks solid matrix under the pressure of tectonic and volcanic internal sources. On the contrary, flux and concentration gas changes in surface waters reveal shifts in those thermodynamic parameters related to permeating fluids. These changes, representing the traditional geochemical research field, are produced by permeability modification induced by stressed rocks fracturing, or by magma migration, or by magma related isotherm moving toward ground (Gaeta etal. [3] and De Natale etal. [4]).

Recent researches have proven the strong potentiality induced by the use of "array" of seismograph to follow seismic and volcanic process evolution (Chouet [5]). This opportunity has not been exploited yet in slow deformation monitoring because of the inadequacy in the few strain meters available for constant monitoring (Linde etal. [6]), which guarantee high precision, but scarce directionality. So far, geophysical and geochemical researches, together with their interpretive models, have followed different ways. On the contrary, a unique vision of mechanic and fluid mechanic phenomena, particularly in the field of volcanology, allows single results to be amplified considerably. Thus, the first objective in volcanology monitoring and research is the production of integrated geophysical and geochemical survey systems.

2 System architecture

Fibre optic sensors represent a unique possibility to realize an "array based" integrated monitoring system.

Regarding strain monitoring, in particular, the possibility to cover with a single type of sensor the whole band of frequencies, from the quasi-static to microseismic represents a great advantage, at large compensating any lack of precision as to the traditional band limited instruments. This kind of broadband sensors guarantees a long step towards the unification of geodesic and seismology investigating fields

The use of optical sensors represents one of the best solutions to satisfy those requests with the great advantages of simple structure, low cost and availability for remote sensing and network architecture.

System architecture will be then composed by two fibre optic sensors networks for strain and gas monitoring, controlled by a Local Monitoring Node (NML) connected to a Regional Data Processing Centre (CEDR), fig. 1.

2.1 Fibre optic strain sensor network

Among several kind of fibre optic sensors developed in the last years, (Measures [7]), Fibre Bragg Gratings (FBG) seem to be the most promising in terms of strain monitoring performance, because: (1) they can be easily embedded in the monitored media; (2) they can be interconnected in series or parallel to realize spatial matrix; (3) they have linear characteristic free from signal amplitude fluctuation; (4) they are highly resistance in sever environment, immune to electromagnetic fields and to high temperature; (5) they are available at low price.

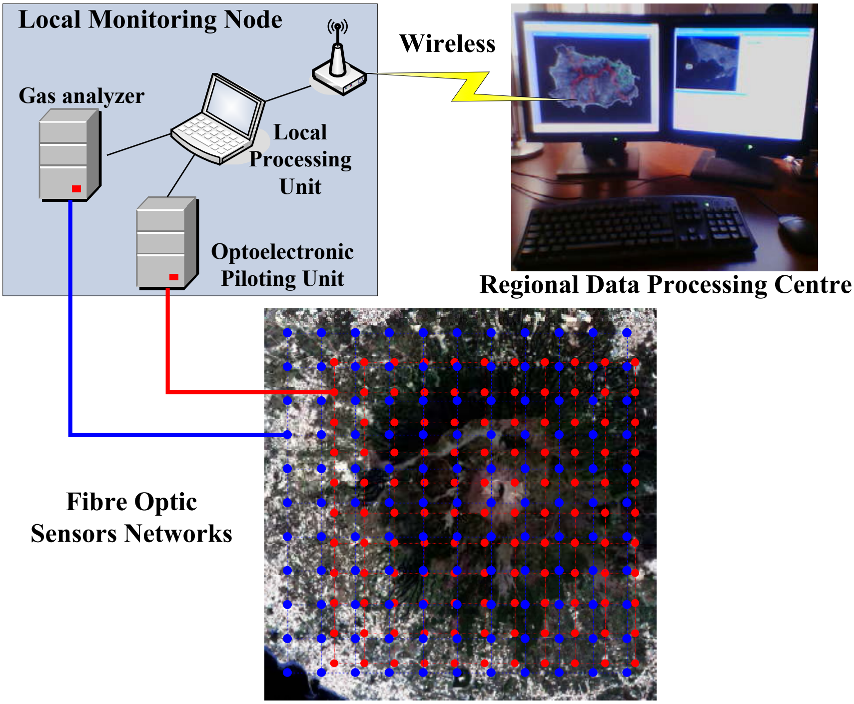


Figure 1: SIMONA project system architecture.

A Bragg gratins consists in a periodic transversal perturbations of the index of refraction along the core of a fibre (Udd, [8]). The grating reflects a spectral peak based on the grating spacing. Thus tension or compression of the fibre will change the grating spacing and the wavelength of light that is reflected back. The measurements of the shift of the reflected spectral peak results in a measurement of the strain, according to the following equation (De Natale and Ferraro [9]):

$$\frac{\Delta\lambda_b}{\lambda_b} = (\alpha + \xi)\Delta T + (1 - p_e)\Delta\varepsilon \,. \tag{1}$$

where $\Delta\lambda_b$ is the Bragg wavelength shift due to temperature (ΔT) and strain ($\Delta\varepsilon$) effects; α is the thermal-expansion coefficient; ξ is the thermo-optical coefficient ($\alpha+\xi = 5.8\ 10^{-6}$ °C^{-1}); p_e is the photo-elastic constant (equal to 0.213). Eqn (1) states that the FBG sensor is sensible even to changes in temperature, as it causes a modification in the index of refraction of the fibre. Thus temperature can be considered an adding noise in the measurement of strain.

2.2 Fibre optic gas sensor network

Optical sensors have acquired great importance in the last years also in the gaseous emission detection in volcanic areas (De Natale etal. [10], Gianfrani etal. [11], [13]). Gas sensors are based on the measurement of electromagnetic attenuation, at a fixed wavelength, due to the interaction between the radiation and the sample to measure. Beer-Lambert law (Mei and Aung, [14]) links the attenuation to the concentration of gases, to temperature and to the length of the optical path. Absorption characteristics are related to the specific molecule, so it is possible to select a molecule by choosing a particular wavelength.

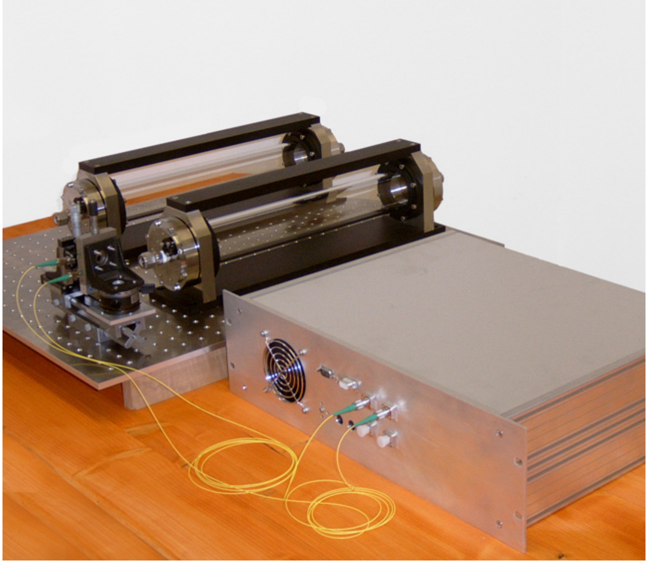


Figure 2: Gas analyzer with CH_4 and H_2S cells, developed by Scienza, Industria e Tecnologia on D'Appolonia design.

Where the chosen source is optical, the radiation is sent from the laser to the fibre, and then to a cell containing the monitored gas (see fig. 2). By using fibre-coupled source, the cells can be very far from the analyzer. Through the use of tuneable lasers, it is possible to scan wavelength emission around the gas absorption frequency centre, and then to reveal signal attenuation at resonance. Resonance condition is obtained through reference cells in the analyzer, containing pure gas. The concentration of the monitored gas is obtained by examining acquired data and comparing them with calibration tables.

During the design phase, two gases have been identified as particularly important for volcanic monitoring, methane (CH_4) and sulphydric acid (H_2S). Gas sensors network is then composed by two separate lines, one for each gas, as two different optical sources are needed. As for CH_4 the absorption line chosen is centred around 1651 nm, while H_2S laser radiation must e centred around 1580 nm. Even the acquiring technique is different: to reveal CH_4 direct technique is sufficient, while H_2S is monitored through two tone technique (Janik etal. [15]).

Cells are multipath, that is in a single 30 cm cell, a series of mirrors is able to realize an optical path of approximately 30 m. Cells are fibre coupled both at the entrance and at the exit, so that a matrix structure can be built around them.

Figure 3: Optoelectronic Piloting Unit, developed by AMS S.p.A. on D'Appolonia design.

2.3 Piloting units

Fibre optic sensors advantages can be really efficient only if supported by proper high-level optoelectronic devices.

In particular a completely new device has been designed and developed for FBG sensors, the Optoelectronic Piloting Unit (UPO, see fig. 3). It is based on a powerful broadband optical source that allows more than 20 FBG sensors on a single channel in a range of 50 km, both statically (frequencies up to 1 Hz) and dynamically (up to 100 Hz) to be interrogated.

The turn key of such unit is represented by new designed high speed devices, an 8 channel optical switch and an Acousto Optic Tuneable Filter (AOTF), which guarantee multiplexing and processing up to 100 kHz. AOTF was presented for the first time in 1999 (Varasi [16]) as a strong device in optical signal processing. It can be configured to work as a conventional Optical Spectrum Analyzer, that is a slow scanner over its wavelength band, and as a filter that can quickly jump across the band. The latter is made possible by the peculiarity of the optical circuit: an AOTF is realized by an X-Cut $LiNbO_3$ crystal. When a sinusoidal voltage is applied at the edges of the crystal, an acoustic wave, and then a wavelength filter, is created inside the optical waveguide. The wavelength position of the filter in modified by modifying sinusoidal frequencies. For this reason the AOTF is driven by a high-speed downconverter frequency source.

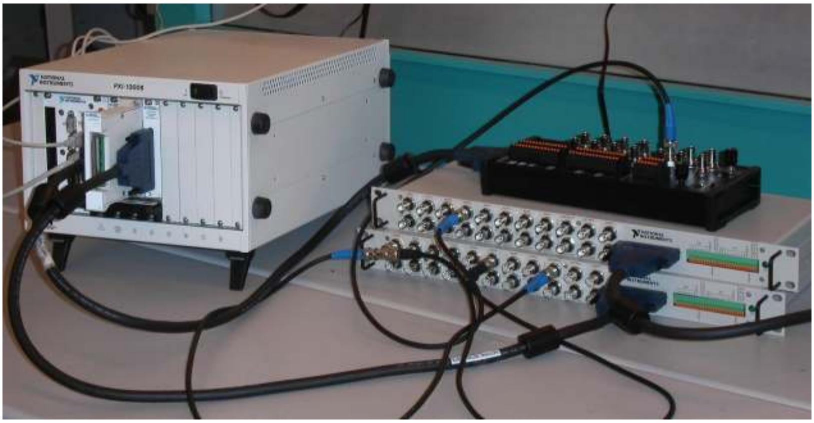


Figure 4: Electronic control unit.

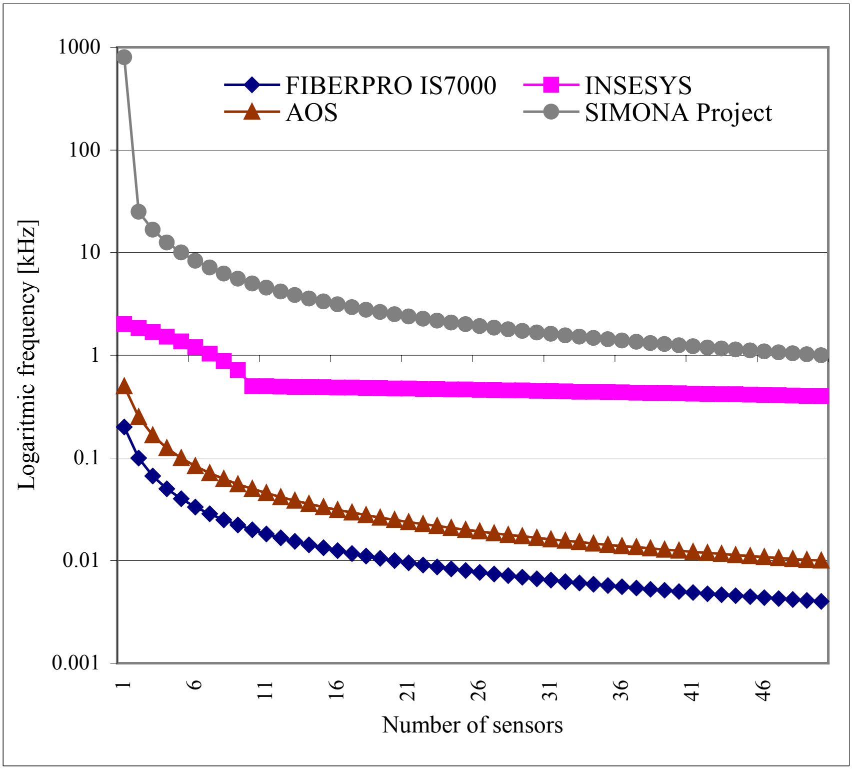


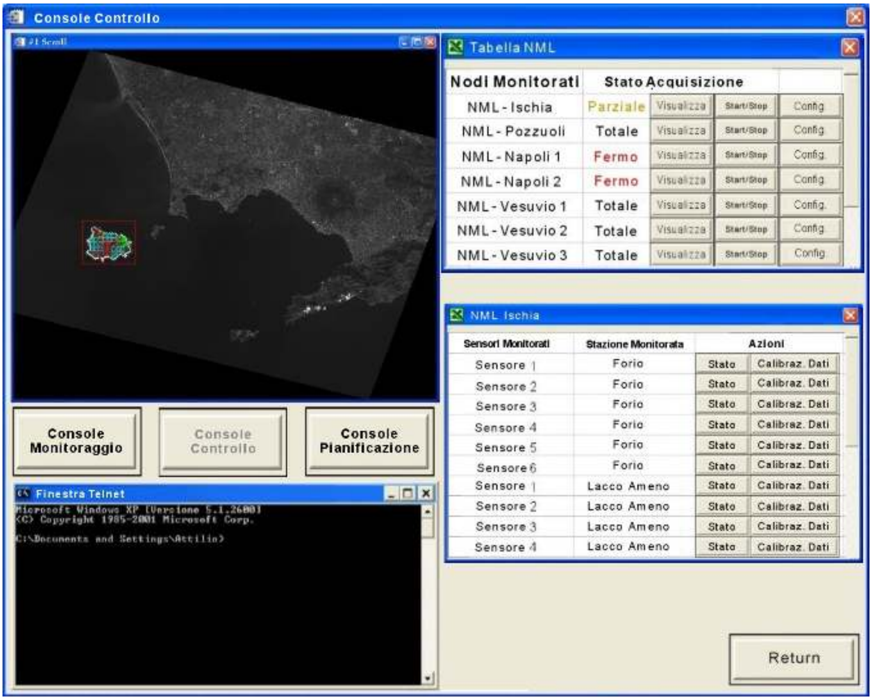
Figure 5: Estimation of the acquisition frequency vs. number of sensors, for SIMONA project and other commercial systems.

Thanks to the innovative components and to the high-speed logic implemented on the Electronic Control Unit (UCE, see fig. 4), the NML is then capable to interrogate FBG sensor up to acoustic frequencies (1 kHz), particularly important because related to rocks microfractures. The maximum frequency of the acquisition depends on the number of sensors (see fig. 5). NML have been designed to guarantee the continuous and contemporaneous acquisition of 48 FBG sensors at dynamic frequency (100 Hz), 48 at static frequency (0.1 Hz), and 48 temperature sensors, to compensate temperature effect according to eqn. (1). FBG sensors on the 8 channel can cover a maximum area of 35 km^2.

2.4 Regional data processing centre

Data integration is firstly realized through the UCE which allows a local operator to acquire and visualize sensors status on a small area.

Further processing, on a larger area, can be made remotely by CEDR. The remote operator is provided with three consoles, with different roles: (1) Monitoring, which allows the operator to visualize nodes status, to zoom over a particular node, and then to command acquisitions; (2) Control, which allows the operator to control the status of a single sensor (see fig. 6); and (3) Planning, which allows the operator to integrate acquired data with a GIS database and visualize them in form of layers.



Nodi Monitorati	Stato Acquisizione			
NML - Ischia	Parziale	Visualizza	Start/Stop	Config
NML - Pozzuoli	Totale	Visualizza	Start/Stop	Config
NML - Napoli 1	Fermo	Visualizza	Start/Stop	Config
NML - Napoli 2	Fermo	Visualizza	Start/Stop	Config
NML - Vesuvio 1	Totale	Visualizza	Start/Stop	Config
NML - Vesuvio 2	Totale	Visualizza	Start/Stop	Config
NML - Vesuvio 3	Totale	Visualizza	Start/Stop	Config

Sensori Monitorati	Stazione Monitorata	Azioni	
Sensore 1	Forio	Stato	Calibraz. Dati
Sensore 2	Forio	Stato	Calibraz. Dati
Sensore 3	Forio	Stato	Calibraz. Dati
Sensore 4	Forio	Stato	Calibraz. Dati
Sensore 5	Forio	Stato	Calibraz. Dati
Sensore 6	Forio	Stato	Calibraz. Dati
Sensore 1	Lacco Ameno	Stato	Calibraz. Dati
Sensore 2	Lacco Ameno	Stato	Calibraz. Dati
Sensore 3	Lacco Ameno	Stato	Calibraz. Dati
Sensore 4	Lacco Ameno	Stato	Calibraz. Dati

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Microsoft Windows XP [Versione 5.1.2600]
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Figure 6: CEDR screenshot of the control console.

The latter console is integrated with new developed inversion algorithm that allows real time data processing in order to estimate the three coordinates of an earthquake centre and the initial time, through two different methods, deterministic (Lay and Wallace [17]), and stochastic or Bayloc (De Natale etal. [18]).

3 Conclusions

SIMONA project presents the following advantages over a traditional seismic network: (1) the possibility to use a single kind of strain sensor to monitor a wide range of frequencies, (2) the possibility to constantly monitor gas emissions, (3) the possibility to install a large network thanks to the lower cost of fibre optic sensors.

Further developments regard (1) the integration with satellite Differential SAR interferometry, to increase its potentiality in monitoring ground subsidence, (2) the conversion of the SIMONA project to the structural application, through the development of proper integrated sensors and inversion algorithm, and (3) the conversion of the SIMONA project to the monitoring of undersea faults.

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