FIRST RESULTS OF A TRI-AXIAL FIBER BRAGG GRATING STRAIN SENSOR

U. Giacomelli[1], D. Carbone[2], S. Gambino[2], E. Maccioni[1], M. Orazi[3], R. Peluso[3], F. Sorrentino[4,5]
[1] *Dipartimento di Fisica, Università di Pisa, Italy*
[2] *INGV - Osservatorio Etneo, Sezione di Catania, Italy*
[3] *INGV - Osservatorio Vesuviano, Napoli, Italy*
[4] *Marwan Technology Srl, Pisa, Italy*
[5] *Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Italy*

Introduction. Rock strains detection is one of the principal ways to monitor geohazards. Stress and strain changes are among the best indicators of impending volcanic activity. In volcano geodesy, borehole volumetric strain-meters are mostly utilized. However, they are not easy to install and involve high implementation costs. Classic strainmeters are cumbersome, hard to install and very expensive. Opto-electronics devices based on Fiber Bragg Grating (FBG) allows an answer to the request of having good sensitivity and easiness of installation, together with reduced overall cost. Moreover fiber optic based devices offer small size, wide frequency band, and even the possibility of creating a local network with several sensors linked in an array. In the framework of the MED-SUV project (MEDiterranean SUpersite Volcanoes, 2013) with the aim of Etna volcano activity monitoring, we have realized, tested and installed a prototype of a tri-axial strainmeter using FBGs. The installation site is Serra La Nave (Catania) about 7 km SW far from the mountain peak, at the premises of the Istituto Nazionale di Astrofisica (INAF) observatory at an elevation of about 1780 m. The device is installed in a 8.5 meters deep borehole. The main goal of our work is the realization of a tri-axial device having a high resolution and accuracy in static and dynamic strain measurements, paying attention to the trade-off among resolution, cost and power consumption. The sensor structure and its read-out system are innovative in their assembly and offers practical advantages in comparison with traditional strain meters. As a demonstration of the performances of our device, the data of the first 15 months of operation are shown.

Sensor description. The sensor is formed by a concrete pillar (40 cm x 10 cm height x diameter) containing three independent orthogonal FBG strain sensors and a temperature probe (Fig. 1). Once cemented in a well, the pillar is deformed by the stress of the surrounding rock and each embedded Bragg probe senses the respective axial strain. The optical signal from the Bragg sensors is linked by an optical fiber cable to a surface opto-electronic read-out system and then acquired. As verified in laboratory tests and confirmed in situ by regional and teleseismic events, this sensor has shown a sensitivity of the order of 10 nanostrains on its vertical axes; 30 nanostrains on the East axes and some hundreds nanostrains on the North axes. The different sensitivity of each axes comes from the non-optimised nature of the individual sensors and of the read-out system. However this first sensor prototype has the aim to trace the road towards second generation systems and now we know which parameters must be tuned to reach the resolution of few nanostrains on each axes. Because of the shallow depth of the well, the performance is limited by the thermoelastic traction effect, that for the three axes ranges from hundreds nanostrains to some microstrain on a daily timescale. Moreover hard-rain events largely affect the signal. To avoid

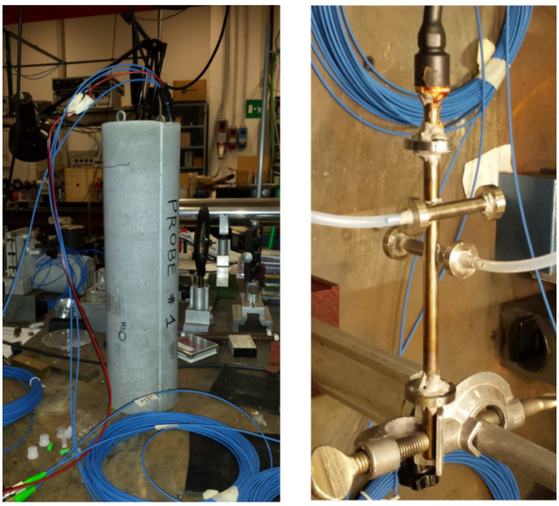

Fig. 1 - Left: assembled sensor. Right: the FBGs before embedding in the concrete pillar.

these spurious effects, second generation sensors should be placed deeper underground, at depth not less than 25-30 meters.

Results and data analysis. On the long period (months, years) the strain values show the expected annual thermoelastic modulation together with a characteristic trend. To understand the components of this behaviour is crucial in working with every borehole instrument. The seasonal thermoelastic traction term is accounted for by a sine wave (one year period), while the remaining trend is of a different origin. In fact it is well known (UNAVCO Workshop, 2012) that there is a combined long-term effect due to two terms: the tendency of the soil to recover the unperturbed situation (that is before the well was drilled), and the curing of the grout used to keep the sensor in close contact with the surrounding rock. On the bases of the experience acquired by the borehole strainmeter community, these last two contributions can be considered by fitting raw data with a function formed by a linear term and an exponential term. In this way the "true" strain is obtained as the fit residual. We used the data from the nearest GPS stations to validate the strainmeter behaviour during a period of about fifteen months (from May 1, 2016 to August 5, 2017). First of all, with a basic approach, we considered the data from two couples of GPS stations, approximately positioned on the North-South and on the East-West directions and with their linking axes crossing the sensor site. In this way, knowing the respective differential movement and the reciprocal distance, it is possible to get an evaluation of the strain along the axes on the horizontal plane. In a second time we have utilised an open-source GPS strain calculator (UNAVCO, 2012) to obtain N-S and E-W strain values of the axes of an ellipse inside a triangle having three GPS stations at its vertexes and containing the installation site position. The centre of this ellipse is the geometrical centroid of the triangle. Because of the nearby GPS stations location, it has been possible to get the centroid position just few hundreds meters a part from our site, and therefore this kind of evaluation is quite representative of the real situation. This calculator requires the geographical coordinates of three GPS stations and their annual average drift velocities along N-S and E-W directions. The principal outputs are the velocity vector of the centroid (described by azimuth angle and modulus), the rotation angle around this point, and, above all, the bi-dimensional strain of the axes of the strain ellipse. In this way we have a complete and reliable description that is very useful to make a comparison with our data. GPS strain results indicate, for the considered time, an expansion in the E-W direction of about 2.1 microstrain (+2.1 $\mu\varepsilon$) and a contraction of 2.5 microstrain (-2.5 $\mu\varepsilon$) along NS. Considering the relation (DeWolf *et al.*, 2015): $\Delta\varepsilon_V = [\, -\nu / (1-\nu)\,](\Delta\varepsilon_E + \Delta\varepsilon_N)$ correlating the strain along the axes (the Poisson's ratio ν may be set equal to 0.25 for this estimation), we obtain also an evaluation of the vertical strain that in this case is of the order of +0.1 $\mu\varepsilon$. Fig. 2 shows Vertical, E-W, and N-S raw data. Looking at our detrended an low-pass filtered data (Fig. 3) we conclude that the EW direction really shows a weak positive trend, while the trend of the NS component is not in accordance with

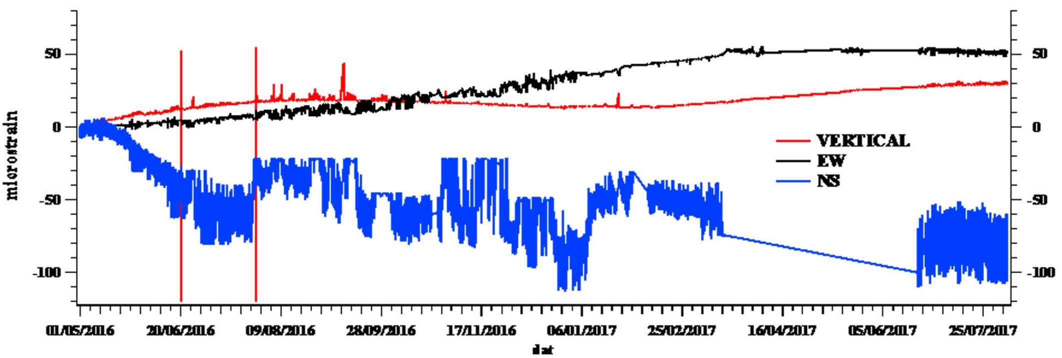

Fig. 2 - Strain raw data.

GPS data. This is not surprising because, as already said, the N-S sensor is largely affected from noise and from poor resolution. Note that the vertical sensor data are in accordance with GPS based calculation: this individual sensor shows the best performance, really allowing a discrimination of a fraction of a microstrain over the whole period. This is a very promising result, constituting an example of what will be obtainable on each axes in second generation sensors. Considering that the data of the vertical axes are still affected by noise coming from the scarce deepness of the well (causing unwanted sensitivity to temperature excursions and to rain events), the potentiality to attain a long term resolution of few tens of nanostrain for each axes is quite clear.

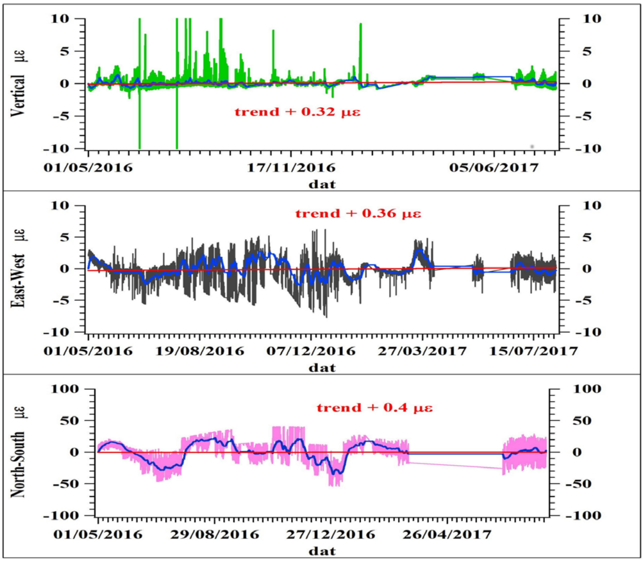

Fig. 3 - Detrended and filtered data.

Conclusions. Our strain sensor prototype has been working for more than fifteen months (data acquisition is still going on) with limited period of default, showing to be a robust and reliable opto-electronic system. As already described elsewhere (Giacomelli *et al.*, 2017), two out of three axes have sensitivity enough to detect regional and teleseismic events, allowing a dynamic calibration. One of the sensors (N-S axes) suffers from poor sensitivity and large noise because of a problem of realisation. Anyway we learned the lesson about that, and we are confident that next generation instruments will be able to attain a resolution at the level of 10 nanostrain on all axes, together with a long term stability good enough to observe tridimensional soil strain.

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