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Real-time signal processing of high-precision borehole strainmeters at Mt. Etna for volcanic surveillance and eruptive events detection

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Summary. — Borehole strainmeter observations at Etna volcano have revealed strain variations associated with volcano activity. In order to automatically identify volcano-related strain changes and track the eruptive activity, we designed the program STRALERT to provide an efficiently filtered strain signal and perform the event detection. By running in near real time, STRALERT contributes to volcanic surveillance operations.

1. – Introduction

Borehole strainmeters are essential instruments for volcano deformation monitoring since they can record volumetric strain changes of the shallow crust due to volcano activity with a high nominal resolution ($\approx 10^{-11}$), unachievable with other geodetic techniques. At Etna volcano, significant strain transients ($>10^{-8}$) due to lava fountain episodes have clearly been observed by the borehole strainmeters [1]. However, ultra-small strain changes ($\approx 10^{-9}$) due to weak eruption activity cannot be easily identified since these are masked by the effect of disturbing strain sources such as Earth tides, barometric pressure variations, rainfall, underground water circulation, etc. [2]. The disturbing signals must thus be filtered to unravel the ongoing deformation processes and correctly monitor volcanic activity. The filtering process can be carried out using programs developed to this end [3, 4]. However, these programs were not designed to be run automatically and thus cannot be directly employed for near real-time monitoring. We developed the program STRALERT to provide in near real time both recorded and filtered signals to the Surveillance Room of the "Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo" (INGV-OE). STRALERT includes the program BAYTAP-G [3] for the signal filtering whose source code was modified to use a pre-defined set of filter parameters. A specific algorithm was designed to automatically detect in near real time strain transients associated with eruption episodes from the filtered signal.

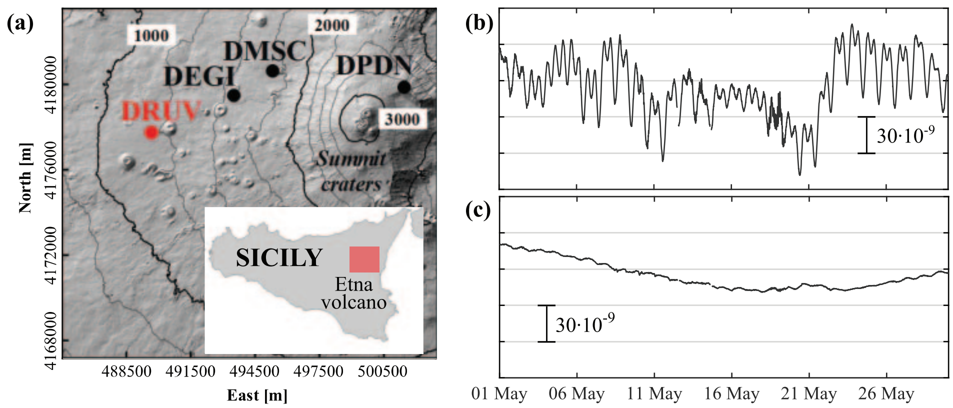

Fig. 1. – Location of the strainmeters at Etna volcano in WGS84 UTM33 (a). Recorded (b) and filtered (c) DRUV signals from 1 May 2020 to 30 May 2020.

2. – Estimation of the filter parameters for near real-time filtering

Four borehole strainmeters were installed at Etna volcano over the last decade (fig. 1(a)) [1]. We focused on the signal recorded by the strainmeter placed at Monte Ruvolo (DRUV) because it is optimally coupled with the rock [1, 5]. We used BAYTAP-G to automatically filter the tidal and the pressure variations using Earth tide theoretical models and barometric measurements [3]. The source code of BAYTAP-G was modified to use pre-estimated pressure coefficients and tidal factors as input filter parameters. We analyzed 14600 different filtering solutions by exploring different input values of both the number of pressure coefficients and the hyperparameter that controls the smoothness of the filtered signal. The goodness-of-fit of the solutions was evaluated with the Akaike Bayesian Information Criterion (ABIC). The pressure coefficients and the tidal factors were estimated in the period 1–30 May 2020 when rainfalls did not occur, the Etna activity was very low and no measurement errors occurred so the recorded signal can be considered mainly induced by the effects of both the Earth tide and the barometric pressure. The efficient filtering process clearly improved the ability of detecting strain changes of low amplitudes. The average value of the standard deviation of the filtered signal (fig. 1(c)) evaluated in moving windows of 3 hours (typical duration of a lava fountain at Etna volcano) is 0.23 nanostrain which is one order of magnitude lower than the one evaluated on the original signal (fig. 1(b)), namely 4.08 nanostrain.

3. – Automatic detection of eruptive events

The filtering process implemented in STRALERT allowed observing strain transients associated with eruptive events that can be masked by the disturbing signals. In fig. 2, both recorded (fig. 2(a)) and filtered (fig. 2(b)) signals are presented for the period 23 June–9 July 2021, in which a series of lava fountain episodes took place [6]. The step-like strain variation corresponds to expansion of the medium around the sensor and can be associated with decompression of the volcano edifice due to the eruption. The recorded signal distinctively shows changes associated with the activity up to the order of 10^{-8}–10^{-7}, while the small strain transients of the order of 10^{-9}–10^{-8} associated with the weaker lava fountains occurring before 1 July are hidden by both the tidal and the

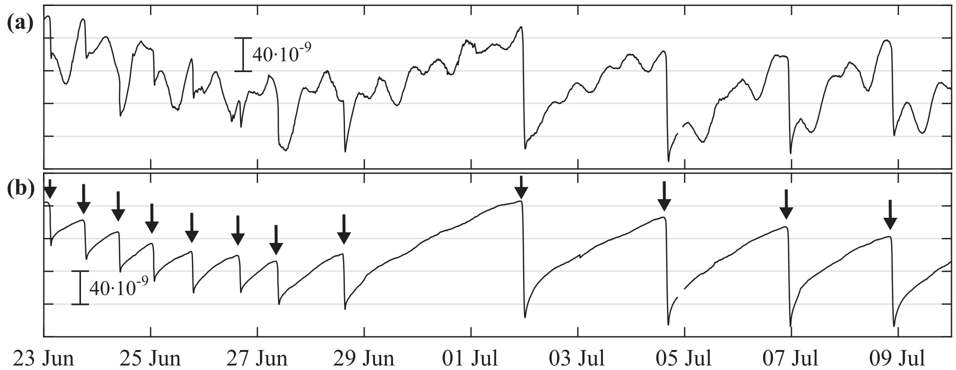

Fig. 2. – The recorded (a) and the filtered (b) strain signals as outputs of STRALERT from 23 June 2021 to 9 July 2021. Arrows indicate lava fountain episodes.

pressure variations. Instead, the filtered signal clearly shows the onset and the end of the small strain variations. We decided to take advantage of this result in order to develop a criterion based on the filtered signal gradient to automatically detect eruptive events in near real time. In reference to the i-th time, we defined the mean gradient $\alpha_{m,i}$ as the slope of the line which interpolates the filtered signal F between the times i and $i - \Delta t$. Moreover, we considered the local gradient $\alpha_{l,i}$ defined for each time l between i and $i - \Delta t$ as the ratio between $F_{l,i} - F_{l-ts,i}$ and t_s, where t_s is the sampling time of the signal. The eruptive event is declared when two conditions are satisfied: 1) the value of $\alpha_{m,i}$ is lower than a threshold α_t; 2) the value of $\alpha_{l,i}$ is always negative in the time interval Δt in order to limit the false positives. A criterion to mark the end of the episode was also developed. One of these two conditions must be satisfied: the value of $\alpha_{m,i}$ is higher than the threshold α_t or the value of $\alpha_{l,i}$ is positive. The best values of the quantities Δt and α_t were estimated by considering two indices: the true positive rate, *tpr*, defined as the ratio between the number of true positives and the number of

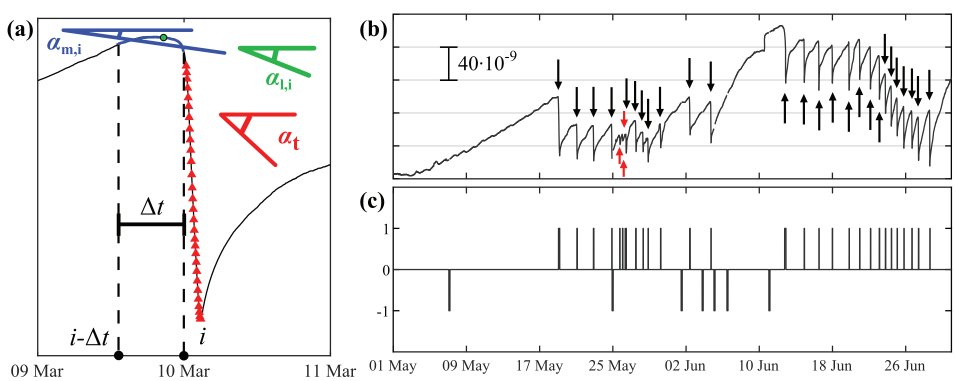

Fig. 3. – The quantities involved for the automatic detection of the eruptive episodes (a). Example of eruption detection for the period 1 May–30 June 2021. Black arrows indicate lava fountains, while red arrows less powerful eruptive events characterized by strombolian activity. The strain changes in the filtered signal (b) are correctly classified as eruptive episodes (c).

eruptive episodes; the false detection rate, *fdr*, defined as the ratio between the number of false positives and the total number of detected episodes. We analyzed the period corresponding to the entire lifetime of the DRUV strainmeter from 20 November 2011 to 31 March 2021 and considered the 71 eruptive events ([7] and INGV-OE reports) that occurred while the DRUV station was in use. The goal was to find the values of Δt and α_t that both maximize *tpr* and minimize *fdr*. We found the best values $\Delta t = 50$ minutes and $\alpha_t = -2$ nanostrain/h which provide $tpr = 1$ and $fdr = 0.64$. To digitalize the information related to the identification of the eruptive episodes, a new signal was defined: the value 1 was assigned when the eruptive event is detected, the value 0 in case of no detected eruptions and the value -1 for data gaps. An example of eruptive event detection is presented for the period 1 May–30 June 2021 (fig. 3(b) and (c)).

4. – Conclusions

The use of the borehole strainmeter signals in near real time is fundamental for monitoring the volcano activity. However, the recorded raw strain signal is affected by disturbances that reduce the ability of detecting small volcano-related strain changes. The program STRALERT was developed to provide in near real time to the Surveillance Room a strain signal efficiently filtered from the effects of the disturbing sources. The careful estimation of the filter parameters of BAYTAP-G, included in STRALERT in an adapted version, allowed to unravel small strain changes associated with the eruptive activity. Thanks to the efficient filtering process, the eruptive events are automatically detected and the information is provided to the Surveillance Room in near real time.

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