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A novel measurement strategy for volcanic ash fallout estimation based on RTD Fluxgate magnetometers

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Abstract *– An innovative solution to measure the fallout of ETNA erupted volcano particles based on Residence Times Difference fluxgate magnetometer is here presented.*
The approach adopted is based on the exploitation of intrinsic magnetic properties of the emitted particles using a FR4 (Flame Resistant 4) fluxgate structure embedding a high permeability magnetic layer (Metglas® ribbon, 1.6 mm thick) between two standard metallized layers.
The proposed measurement system, for volcanic ash fallout estimation, represents an innovative direct sensing methodology, different from other current approaches that generally estimate the material in suspension and evaluate the expected fallout by using numerical models, such as satellite imaging, radar observations, Geostationary Operational Environmental Satellite, Moderate Resolution Imaging Spectroradiometer and the Atmospheric Infrared Sounder.
The experimental set-up is here described and some preliminary results are reported to show the suitability of the approach proposed.

Keywords *– RTD-Fluxgate, volcanic ash fallout estimation.*

I. INTRODUCTION

Volcanic particles are formed when volatiles dissolved in magma at high pressure, expand and escape violently into the atmosphere. This natural phenomenon, that forms eruption columns, is called explosive volcanic eruption [1]. Volcanic particles can be composed from a great variety of particles (e.g. juvenile fragments, crystals, minerals, lithics) with different size, shape and composition. The dimension of these clasts ranges from blocks or bombs (>64 mm in diameter) to ash (< 2 mm in diameter), that can reach sizes of the order of micrometers. Volcanic ash contains silica, aluminium, magnesium, iron, potassium, sodium, calcium, and other minor elements; it is hard, does not dissolve in water, is highly abrasive, conducts electricity only in wet condition and presents intrinsic magnetic properties.

Volcanic ash represents a serious problem for the public health; in fact it can be inhaled deeply into the lungs and therefore cause respiratory problems [2]; it can be the source of several ophthalmology problems and a component of crystalline silica called cristobalite can cause silicosis. Further volcanic ash causes water contamination [3], represents a serious hazard for aircrafts flying or landing in the area interested by the volcanic plume and, finally, can increment automobile accidents [4].

It is therefore of primary importance to have as much as possible information on the area covered from the fallout that strongly depends on the style of explosive activity and on the actual meteo-climatic conditions.

Several methodologies have been recently proposed to tackle this goal: suitable tephra dispersal models have been developed to forecast the plume movements and the associate tephra fallout; remote sensing techniques such as satellite images obtained by the Geostationary Operational Environmental (GOES) [5] and by the Meteosat second generation satellites (MSG), radar observations, lidar instruments show to have interesting performances on the detection of volcanic ash in atmosphere. For example, meteorological satellites are very useful for the observation of volcanic ash by using the brightness temperature difference between two thermal infrared channels peaked at 10–12 μm (also known as split window algorithm). This difference can be used to discriminate clouds containing volcanic ash particles and those containing water droplets or ice crystals [6].

However, satellites are able to detect only the smallest particles (order of micrometers), that are mainly located in atmosphere but can have serious difficulties when they have to describe the fallout in the nearest area from the volcanic vent.

The knowledge of this latter information is of primary importance for social security management of the crisis phase during the explosive eruptions. Only recently an X-band disdrometer was tested to measure the particle fallout in the 2002-03 Etna eruptions [7]. Indeed, new instruments should be used to obtain more reliable information on particle fallout for validating tephra dispersal models.

In this paper an innovative solution to directly measure the fallout of erupted volcanic particles is presented. The measurement strategy proposed is based on RTD-Fluxgate magnetometers that have been developed by the authors [8] and on the exploitation of magnetic properties of volcanic particles.

The problem of measuring the actual fallout of volcanic particles is not trivial due to a list of reasons among which the high resolution required to the measurement system and the high selectivity to be achieved. In fact it is important to be able to deal with very small volumes of particles deposited over a given area: a high resolution is required to the measurement systems in this field. The task of measuring small volumes of ash is made even more difficult by the contemporary possible presence of other substances (for example normal sand or water from rain): therefore sensitivity is the other major characteristic to be addressed.

The approach presented in this paper is based on the exploitation of intrinsic magnetic properties of the volcanic particles to be detected, in fact basaltic volcanic particles show a paramagnetic behaviour and therefore they can be isolated in a generic sample from the other substances by using a biasing magnetic field. The magnetic signal thus produced is however weak and consequently a very large resolution is required to the DC magnetometer together with high sensitivity and low noise level. Further, low cost and power budget are also desired features because large number of such measurement systems should be distributed over very wide area.

The technological approach is based on the realization of a dedicated set-up including a FR4 (Flame Resistant 4) fluxgate. Actually a modified structure embedding a high permeability magnetic layer (Metglas® ribbon, 1.6 mm thick) between two standard metallized layers is used to construct the Fluxgate magnetometer and to realize the measurement system needed for volcanic ash fallout estimation.

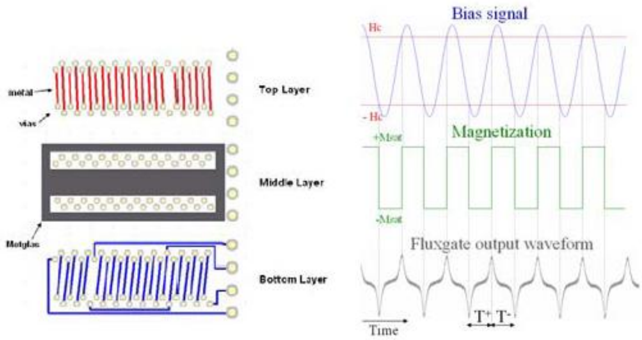
II. THE PROPOSED MEASUREMENT APPROACH: THE FR4-FLUXGATE MAGNETOMETER

The Residence Times Difference (RTD) Fluxgate magnetometer represents an innovative solution to detect quasi static magnetic field. Fluxgate magnetometers represent an alternative solution to sense low magnetic fields or magnetic field perturbation, at room temperature. Recently, the authors have proposed Residence Times Difference (RTD) fluxgate as competitive devices to the traditional second harmonic architectures [9, 10]. The main advantages of this innovative readout strategy are low cost, small dimension, high sensitivity, low noise floor, low power consumption and an intrinsic digital form of the output signal.

The RTD-Fluxgates find applicability in fields such as space, biomedical, vehicle navigation, security, military, geomagnetic field measurement and proximity applications [11, 12].

Typically the RTD-Fluxgate is based on two coils architecture (excitation and detection coils) shown in Figure 1a. The coils are wound around a suitable ferromagnetic core showing a sharp hysteretic input-output characteristic which allows to infer that switching between the two stable states of the magnetization occurs instantaneously when the applied magnetic field exceeds the coercive field level H_c. A periodic driving current I_e is applied in the excitation coil and generates a periodic magnetic field H_e parallel to the geometry of the core. The target magnetic field H_x is applied in the same direction of H_e; the secondary coil is used as detection coil and the fluxgate output voltage V_{out} is proportional to the first derivative of magnetization, and contains the external magnetic field information (Figure 1b).

The Residence Times Difference Fluxgate working principle is based on a time domain readout strategy. The idea is to exploit the information carried out by the time position of spikes in the V_{out} signal (Figure 1b). Time intervals, T^+ and T^-, defined by two successive peaks represent times spent by the core magnetization in the two steady states assuming a bistable potential function to describe the hysteretic core. These time intervals are called Residence Times then the Residence Times Difference is the quantity $RTD = T^+ - T^-$.



(a) (b)

FIGURE 1. a) The RTD-Fluxgate sensor structure. b) The sinusoidal bias signal, evolution of magnetization and the corresponding fluxgate output voltage signal.

The RTD expression for a sinusoidal bias signal can be computed [9] from the following equation as a function of the target unknown magnetic field H_x:

$$RTD = \frac{2}{\omega}\left[\arcsin\left(\frac{H_C + H_X}{H_e}\right) - \arcsin\left(\frac{H_C - H_X}{H_e}\right)\right] \qquad (1)$$

where H_c is the coercive field of the magnetic material used for the sensor core while H_e is the excitation magnetic field having frequency $f=\omega/2\pi$.

Recently the authors have paid significant efforts to the realization of novel fluxgate prototypes that use new materials and different technologies. One of these approaches is based on a modified Printed Circuit Board (PCB) strategy that embeds a suitable magnetic layer into a metallized FR4 sandwich [13]; moreover a lot of work is currently in progress on wire-core fluxgates that use a 100 μm magnetic wire as core.

Finally some other efforts are being paid to the integrated release of RTD fluxgate magnetometers.

The scientific literature reports several interesting results in this area [14, 15] that however mainly address geomagnetic field.

Figure 2 shows an image of FR4 RTD Fluxgate prototypes having different shapes and dimensions. A complete characterization of a FR4-Fluxgate prototype was performed in [16]. The device shows a sensitivity of 0.7 μs/nT and a resolution of 1 nT @ 80 Hz, 20 mA_{pp}.

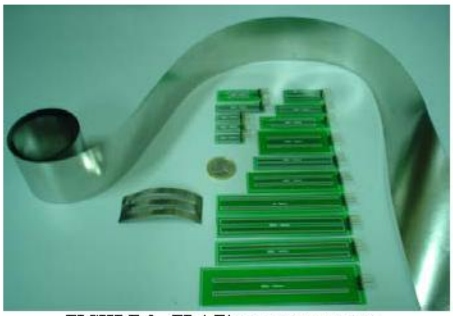


FIGURE 2. FR4-Fluxgate prototypes.

The novelty introduced in this paper is to measure the actual fallout of volcanic ash is based on FR4-Fluxgate and exploits the intrinsic magnetic properties of these volcanic particles.

The Flame Resistant 4 (FR4) fluxgate magnetometer is realized by adopting a patterned internal layer of amorphous ferromagnetic core, Magnetic Alloy 2714 As Cast (Cobalt based), by Metglas® having a sharp hysteretic characteristic. In the process a patterned Metglas® foil (magnetic Alloy 2714 As Cast Cobalt based, by Metglas®) is embedded between two FR4 PCB layers. A simplified process description can be summarized by the following steps: 1) the patterned Metglas® is aligned respect the two FR4 layers; 2) the patterned metal layers are aligned to the sensor structure according to layout design; 3) the layers are then pressed, while heating the whole system up to 200 °C; 4) the vias formation between the lower and upper layers let to complete the windings for the coils.

III. EXPERIMENTAL SET-UP AND RESULTS

The measurement system proposed here is made by a plastic pipette where the sample of volcanic ash to be measured is collected; a permanent magnet to polarize the volcanic ash; a Plexiglas support platform to firmly hold in place the Fluxgate magnetometer and all the other components. The measurements are performed inside a three-layer MATGLAS magnetic shield and the output signals are processed via a labVIEW procedure. Pictures of the experimental setup are reported in Fig.3a and 3b.

The RTD-Fluxgate magnetometer is used to detect the volcanic ash disposed over the bottom surface of the plastic pipette (a permanent magnet is used to polarize the volcanic ash). The fluxgate is operated with a sinusoidal bias signal of 20 mA_{pp}@80Hz. The fluxgate and the biasing permanent magnet are placed on the opposite sides of the small pipette where the volcanic ash volume to be measured is conveyed.

(a) (b)

FIGURE 3. a) The measurement system for volcanic ash fall out estimation. b) Experimental set-up to estimate the ETNA volcanic ash.

The experiments have been conducted by observing the Fluxgate output signal for different values of volcanic particle volumes (Figure 4). Each sample quantity is maintained in the measuring position for 150 s.

The experiment has been conducted by observing the Fluxgate output signal for different values of volcanic particle volumes (Figure 4). Each sample quantity (corresponding to 5 ml, 4 ml and 3.5 ml, respectively) is maintained in the measuring position for 150 s. An increment of the variation of the RTD value between a zero target condition and the considered target condition is observed for increasing values of the ash volume.

Several samples with different granulometry and related to different Etna volcano eruptions have been provided by the Instituto Nazionale di Geofisica e Vulcanologia (INGV), sezione di Catania.

IV. CONCLUSIONS

The approach shown here for the measurement of actual volcanic ash fallout is very promising for the real time measurements of the volcanic activity and consequently could have a great impact from a point of view of the social health and security. Moreover the measurements gathered by using the system proposed can be profitably used to validate the numerical models used for simulating the fallout prediction from Etna explosive eruptions.

The measurement system for volcanic ash fallout estimation based on RTD-Fluxgate magnetometers represents an innovative directly sensing methodology, different with respect to the systems used up today.

The RTD-Fluxgate magnetometers have also low cost, small dimension, high sensitivity, low noise floor and low power consumption system. In practice the measurement system proposed can be disposed on a particular area of interest, adopting a single fluxgate magnetometer, to estimate the volcanic ash, or creating a distributed fluxgates-based network to monitor eruptive phenomena in a wide area of interest. The results obtained encourage further effort for increasing the efficiency of detection strategies based on RTD Fluxgates.

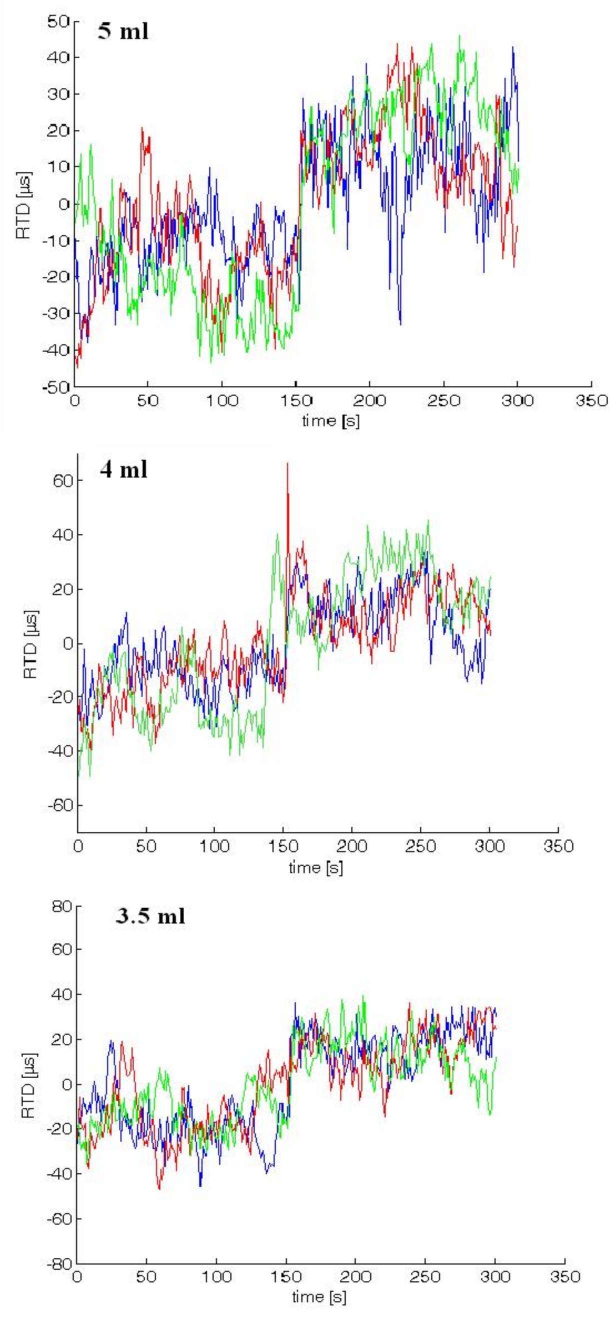


FIGURE 4. Variation in the RTD value for different volcanic ash volumes. The actual output signal of the RTD fluxgate is shown (the sample volume is applied after 150 s).

Future activities will include analysis and estimation of volcanic ash mixed with rain, sand, non magnetic ash and finally measurement system based on microwire-Fluxgate to detect small quantities of volcanic ash.

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