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Monitoring the Reawakening of Canary Islands' Teide Volcano

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Following more than 30 years of seismic and volcanic quiescence, the Canary Islands region located off the northwestern coast of Africa started to show signs of seismovolcanic activity at the end of 2003 (Figure 1). In spring 2004, there was a significant increase in the number of seismic events (a mixture of volcano-tectonic events and regional earthquakes with pure volcanic events such as tremors and long-period signals) located inland on Tenerife Island.

The increase ofactivity in 2004 coincided with an increase of fumarolic activity at the Teide volcano on Tenerife Island, an increase in the emission of carbon dioxide in the northwestern part of the island, and changes in the gravimetric field on the northern flank of the volcano. After several seismic events had been felt by the population, the first alert level was declared by the civil protection division of the local government. This apparent reawakening of Teide, which last erupted in 1909, provides an opportunity to study from the initial stages the reactivation of this volcanic area and its related phenomena.

This article presents an automatic seismic monitoring system, the Teide Information Seismic Server (TISS), that is monitoring the internal status of the volcano by means of real-time seismic background noise analysis. The system's main goal is to detect precursors to a potentially dangerous eruptive episode at an early stage. The system, in operation at Teide volcano since November 2004, has proven useful in monitoring changes in the behavior of the volcano's processes, such as fumarole venting and seismic activity. These external manifestations of the volcano's processes have been preceded by changes in the monitored parameters (see Figure 2).

A Brief History

Several eruptions have taken place in the Canary Islands in the last 500 years, all of them of the effusive type, where lava flows freely without explosive power. Teide (28.27°N, 16.6°W) is a complex stratovolcano, the third-tallest volcano on Earth from base to tip, reaching an altitude of 3717 meters above sea level and approximately 7000 meters above the adjacent seabed. Teide's last explosive-type eruptions have been dated as having occurred around 1500 years ago. Future eruptions are considered likely and will include the risk of highly dangerous pyroclastic flows similar to those on Mount Pelée (Martinique) and Mount Vesuvius (Italy). The Teide volcano's explosive eruptions are the result of magma mixing processes in which basaltic eruptions act as a triggering mechanism.

In 1990, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) identified Teide as being worthy of particular study in light of its history of large, destructive eruptions and its proximity to populated areas. For the present high-risk level, since 1992 Teide has been considered by the IAVCEI as one of the European Laboratory Volcanoes, thus receiving special consideration from the European Union concerning research proposals.

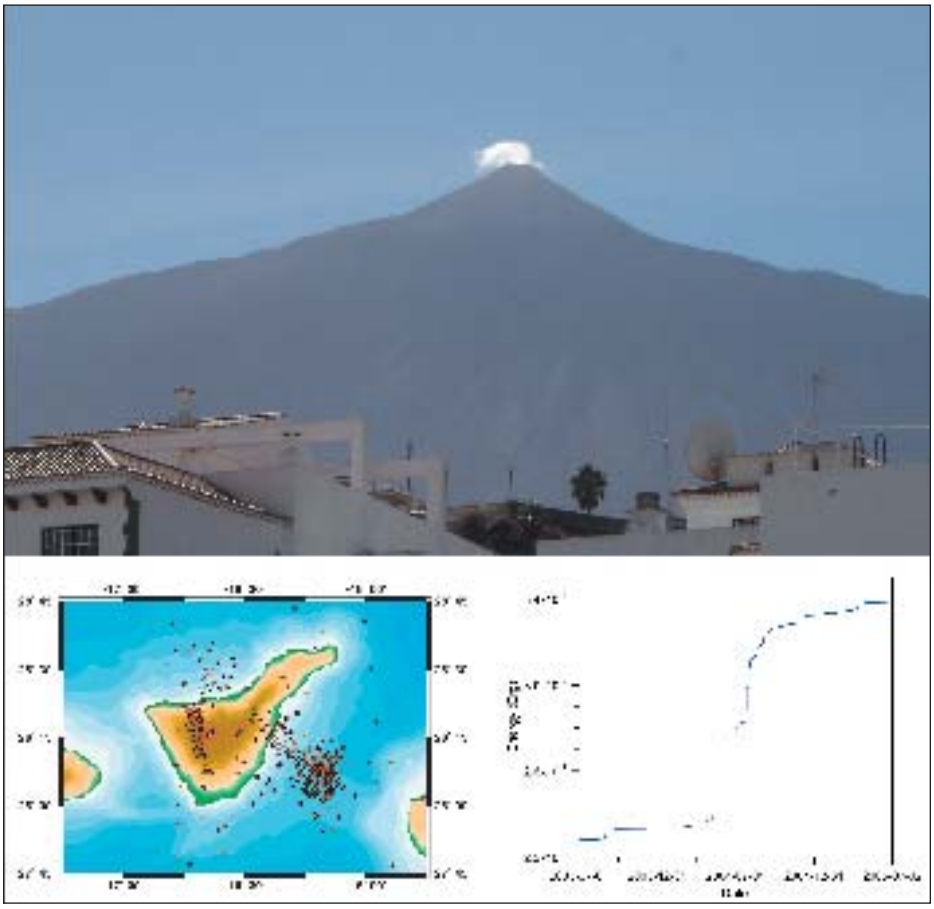

Fig. 1. (top) Signs of activity at the Teide volcano (October 2004). Picture provided by the municipal government of Icod de los Vinos (Tenerife, Canary Islands, Spain). (bottom left) Epicentral locations of events from January 2000 to June 2005. Red dots indicate events from May 2004 to July 2005. (bottom right) Evolution of the cumulative seismic energy released by earthquakes located inland on Tenerife (data provided by the Spanish Instituto Geográfico Nacional).

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TEGETEIDE Project

The special topographic characteristics of the Canary Islands, combined with the distribution of the islands' more than two million inhabitants, increase the level of volcanic risk in this area. A Teide eruption similar to the last dated explosive type eruption (with a volcanic explosivity index (VEI) of 3) and comparable with the last eruptions of Unzen Volcano in Japan could affect up to 30,000 people; a VEI of 4 could affect more than 400,000 people.

The reported increase in seismic activity that has been observed since spring 2004 could represent the beginning of a reactivation of Teide Volcano. An urgent call by the Spanish government to the Spanish National Commission on Seismic and Volcanic Risk Evaluation to organize and manage the available scientific resources to evaluate the possibility of an imminent eruption has been considered. As a result of this call, financial support for research projects on this area was provided, and in the spring of 2005, the Spanish National Research Council (CSIC) initiated the TEGETEIDE project (Geophysical and Geodetic Techniques for the Study of the Teide-Pico Active Volcanic Area) .

This project will develop and implement TISS, which is capable of characterizing the predominant frequencies and the seismic energy released that is observed in the background seismic noise at diverse frequency bands. TISS is capable of monitoring in real time changes of the status of the volcano by collecting information in the time and the spectral domains, using parameters in which changes due to variations in the recorded signals are easy to observe. The goal is to detect changes before the expected episodes of activity.

TISS is based on a real-time quality-control (RT/QC) analysis of continuously-collected waveform data from seismic stations, and it monitors changes in the behavior of the seismic signals. These changes reveal variations in local site effects caused by changes in the volcanic activity. The present TISS process involves two different stages: The first stage, termed 'data preparation,' and the second stage, called 'data analysis.' The main tasks in data preparation are to build the basic data format and to provide visual Live Internet Seismic Server-like outputs (http://www.liss.org). The data analysis stage, which is devoted to waveform analysis, selects fixed-length segments from the already established database, assigns time stamps, and applies subroutines of spectral analysis.

The current RT/QC analysis was developed in 2002 to test permanent stations at the Observatori Fabra in Barcelona, Spain [*Llobet et al.,* 2003]. Its expansion to large networks was accomplished in 2004 when an adaptation of the QC procedure was developed [*Sleeman and Vila,* 2006] to monitor all stations of the Virtual European Seismic Network [*Van Eck et al.,* 2004]. Its off-line application for monitoring changes in background noise near active volcanoes is presented by *Vila et al.* [2005], who showed that continuous monitoring of the background seismic noise levels may provide signs of activity more than 40 days sooner than classical seismological methods based on earthquake analysis.

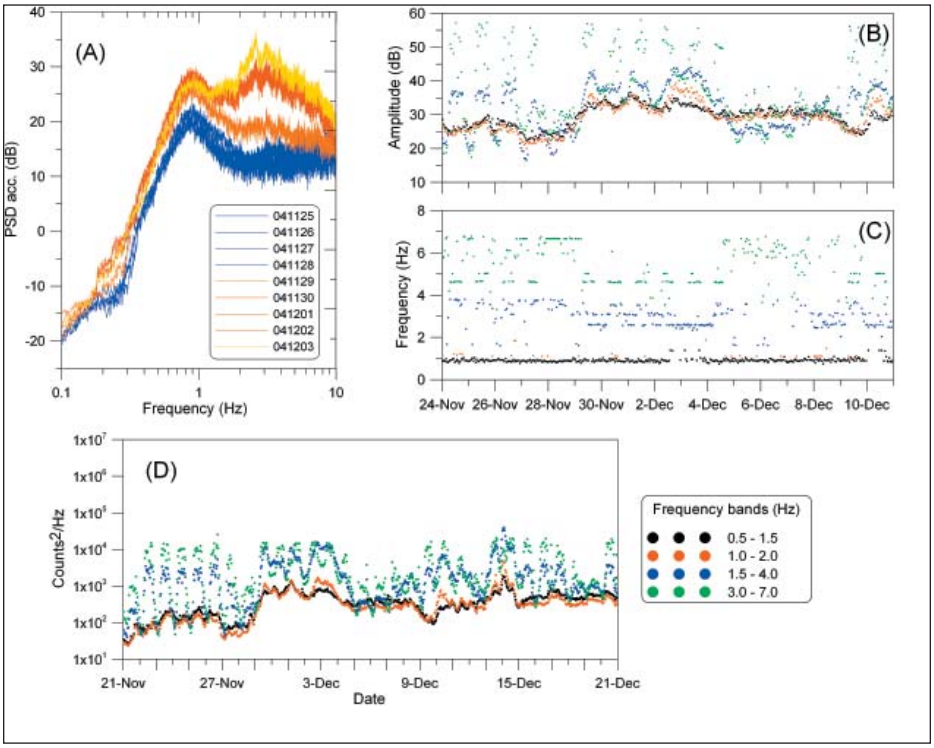

Fig. 2. Variations in parameters provided by TISS before and after the appearance on 5 December 2004 of the fumarole emission in La Orotava Valley: (a) Daily lower envelope of all 60-minute PSD curves; (b) Evolution of the amplitude; (c) Predominant frequency; (d) Integrated PSD amplitude. Plots (b), (c), and (d) relates data in four frequency bands.

The adaptation of TISS for the Canary Islands uses a power spectral density (PSD) estimation to perform spectral analysis of the continuously incoming data [*Welsh,* 1978]. TISS computes the PSD of 60-minute segments, extracted from the pool of continuous data, and stores selected parameters as time series. These time series are selected frequencies of the PSD, integrated PSD in various frequency bands (energy related parameters), and absolute maximum PSD amplitude and its corresponding frequency, also in various frequency bands. Moreover, the lower envelope of all the PSD curves (minimum value for each frequency) obtained after processing time intervals of 24 hours is tracked, thus giving an estimation of all nontransient signals during one full day of operation. This envelope contains the noise that is always present at every frequency component [*Vila et al.,* 2005] and is continuously compared with previous days. TISS provides details of the evolution of this information by means of report plots.

The post-analysis derived time series have a sampling rate of the order of one sample per hour, determined by the length of the segments analyzed. These time series are then suitable to be compared directly with many other signals, such as deformation, temperature, and gas emission, that are sampled at similar sampling rates, thus resulting in a multidisciplinary analysis. The sampling rates of the post-analysis derived time series also allow a fast and easy representation of the volcano's seismic activity. The time series also can be used as new input for any supplementary near-real-time analysis. This corresponds to the third level of observatory automatic procedures [*ESF-EVOP Working Group,* 1994].

Evaluation of TISS During 2004

Since first becoming operational in November 2004, TISS has shown itself to be very useful for monitoring changes in the behavior of the Teide volcano's processes, such as fumaroles and seismic activity. For example, on 5 December 2004 a new fissure with fumarole emission appeared in La Orotava valley, on the northeastern flank of Teide volcano (see Figure 2). This was preceded by a significant increase in low-frequency seismic energy nine days earlier, with a return to the normal level a few hours after the fissure aperture. During those nine days, the scientific team remained on alert.

TISS archives the original time series data in standard formats such as SEED (Standard for the Exchange of the Earthquake Data) or GSE (Group of Scientific Experts) and is thus a complete and open system that allows the data to be processed by means of standard seismological software packages. The software package runs under Linux, and all software used can be obtained through GNU and other free software sites. There are no intrinsic limitations for the number of chan-

nels or computations. The performance analysis of the system reveals that a 1.2 GHz Pentium III personal computer can handle more than 400 channels at 100 samples per second.

Sources of data and programming facilities can be found on the TISS Web pages (http://www.sistegeteide.info/tiss and http://sismic.am.ub.es/tiss). Examples of RT/QC implementations are available at http://sismic.am.ub.es/ISEV/ and http://www.orfeus-eu.org/data-info/dataquality.htm.

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Adam Paulsen, a Pioneer in Auroral Research

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The 20 to 30 years following the first International Polar Year in 1882–1883 was a period of quickly advancing knowledge and understanding of auroral phenomena. This was the time when hypotheses of aurora being due to, for example, reflections of fires from the interior of the Earth or sunlight from ice particles were abandoned and replaced by the mechanism of precipitating electrons.

One of the auroral researchers at that time was the Dane Adam Frederik Wivet Paulsen (1833–1907). However, when reading literature about auroral history, his ideas and work do not seem to have attracted much interest outside his own and neighboring countries. For example, in his sweeping historical account *Majestic Lights: The Aurora in Science, History, and the Arts* [1980], author Robert Eather only referred to Paulsen in a couple of lines.

Eather did not mention any of Paulsen's original and still valid ideas, namely, that electrical currents flowing parallel to the Earth's magnetic field exist and move upward within the auroral bands, that the aurora is produced by cathode rays (electrons), and that the source of the cathode rays is located in the upper regions of the Earth's atmosphere. The purpose of this article is to draw attention to Adam Paulsen and his contributions to the understanding of the aurora.

Paulsen and the 1882–83 Expedition to Greenland

Paulsen was born on 2 January 1833 in Nyborg, Denmark. He had planned to be an officer in the Danish army, and from 1849 to 1851 he participated in a war against Germany. However, an interest in physics changed his career path. Adam Paulsen earned a master's degree in physics in 1866 from the University of Copenhagen, Denmark, and two years later he was awarded a gold medal by the same for a prize essay on the different theories of galvanism (electricity produced by chemical processes).

Fig. 1 Adam Paulsen, age 67. The pencil drawing (25 x 30 cm) was made by Harold Moltke on 10 February 1900 during Paulsen's expedition to Akureuyi, Iceland.

After completing his university studies, Paulsen became a high school teacher in Copenhagen. In 1880, at the age of 47, he quit teaching after he was asked by the director of the Danish Meteorological Institute to head a Danish expedition to Greenland during the upcoming Polar Year. Denmark, as part of an international consortium that had pooled their resources to study the Arctic, was to conduct meteorological, geomagnetic, and auroral observations (including the shape, color, strength, movement, and position of aurorae). Paulsen, along with five other men, sailed from Copenhagen aboard the Royal Greenland Trade Department's small three-masted sailing ship *Ceres* on 17 May 1882, bound for Godthaab (64°10'N, 51°40'W), a small town on the west coast of Greenland. After a four-week voyage they arrived at their destination.

The location was found favorable for auroral observations. Godthaab is located just on the poleward side of the belt of maximum auroral activity, an area advantageous for the study of the periodic variations of auorae. The team also planned to investigate relationships between the aurora and magnetic disturbances, and to attempt to measure the height above the ground of the aurora, because such knowledge might help to disclose its causal mechanisms.

The height measurements were not successful, because the distance of about five kilometers between two observation sites on the ground was much too short for a good quality triangulation to be made. However, the study of the relation between aurora and magnetic disturbances inspired Paulsen to suggest that field-aligned currents exist. This was a milestone in auroral research.

The expedition team returned to Denmark in the autumn of 1883, and the following year Paulsen became the director of the Danish Meteorological Institute, a position he held until his death in 1907.

Paulsen's Discoveries

In a comprehensive report about observations during the International Polar Year and the following years in Greenland, *Paulsen* [1893] presented, among other discoveries, observations indicating the existence and

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