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A rapid deployment instrument network for temporarily monitoring volcanic SO_2 emissions – a case study from Telica volcano

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Abstract. Volcanic gas emissions play a crucial role in describing geophysical processes; hence, measurements of magmatic gases such as SO_2 can be used as tracers prior to and during volcanic crises. Different measurement techniques based on optical spectroscopy have provided valuable information when assessing volcanic crises. This paper describes the design and implementation of a network of spectroscopic instruments based on differential optical absorption spectroscopy (DOAS) for remote sensing of volcanic SO_2 emissions, which is robust, portable and can be deployed in relatively short time. The setup allows the processing of raw data in situ even in remote areas with limited accessibility, and delivers pre-processed data to end users in near real time, even during periods of volcanic crisis, via a satellite link. In addition, the hardware can be used to conduct short-term studies of volcanic plumes in remote areas. We describe here tests of the network at Telica, an active volcano located in western Nicaragua, during three different measurement periods, including an eruptive crisis. The tests produced what is so far the largest data set of continuous SO_2 flux measurements at this volcano. The measurements show that, during the period 2010–2013, the flux averages approximately 100 tons per day ($\mathrm{t\,day^{-1}}$).

1 Introduction

Volcanic gas emissions play a very important role as a tracer of volcanic activity, thus providing valuable information for scientific purposes and risk assessment (Symonds et al., 2001). In particular, increases in SO_2 emissions have been largely associated with magmatic inputs to shallower levels; this process plays an important role in controlling eruptive events, as demonstrated by studies conducted during periods of enhanced volcanic activity (e.g. Casadevall et al., 1983; Olmos et al., 2007; Malinconico Jr., 1979; Zapata et al., 1997).

Traditionally, volcanic gases have been studied by in situ sampling, implying the need to have direct contact with the source of emissions. Such proximity hinders research work due to the hazardous nature of working close to an active volcanic vent. The tragic incident at Mount Galeras in 1990, where six researchers were killed during an unexpected eruption, illustrates this reality.

Optical remote sensing techniques rely on the spectroscopic characteristics of the gases. These methods can measure these signals from afar, offering an attractive and safer option for volcanic gas monitoring, including satellite imagery and ground-based remote sensing. Satellite imagery has been applied for detecting and tracking volcanic plumes even in very remote areas (e.g. Campion et al., 2010; Henney et al., 2012; Urai, 2004). However, satellite imagery has limited spatial and temporal resolution, and the high detection limits only allow monitoring of major eruptive events and/or volcanoes with considerable gas emissions.

Ground-based optical remote sensing techniques have provided a more feasible alternative for monitoring volcanic gas and include mobile and stationary measurements. Mobile measurements beneath volcanic plumes have been made successfully worldwide (e.g. Galle et al., 2002; Hoff and Millan, 1981; McGonigle, 2005); however, their temporal resolution is limited due to the impracticability of performing continuous measurement traverses, especially in areas with limited accessibility. On the other hand, stationary optical scanning instruments are able to perform continuous measurements, thus improving the time resolution (Edmonds et al., 2003). This approach has been extended with the aim of monitoring gas emissions on a global scale; hence, the Network for Observation of Volcanic and Atmospheric Changes (NOVAC) project is monitoring about 20 volcanoes around the world using optical scanning instruments (NOVAC instruments), providing an exceptional data set of volcanic gas emissions (Galle et al., 2010).

Nevertheless, setting up a permanent NOVAC instrument may be challenging in certain circumstances. A typical installation can take from a few days up to several weeks, depending on the geographic and logistic conditions, hence requiring very careful planning. Moreover, in some cases, volcanic crises occur unexpectedly, with minimal precursory signals. Setting up a monitoring network under such circumstances adds to the difficulties because time becomes a critical parameter.

These technical advances and field challenges have led to the idea of a rapid deployment system (RADES) for volcanic gas monitoring using optical scanning NOVAC instruments. Rapid deployment networks for volcanic surveillance during crises have been proposed before, but the success of this idea was limited by the technology at that time (e.g. Tárraga et al., 2001). Recent technological improvements, which include low-cost embedded electronics, have made it possible to build a network with such characteristics.

The RADES consists of a set of compact and portable modules that prior to and during an imminent volcanic crisis can be deployed quickly, to set up a local wireless network of instruments that includes scanning differential optical absorption spectroscopy (DOAS) for SO_2 measurements and a hub for satellite data transfer. This network provides near-real-time data to local authorities who can then evaluate and monitor the progression of a volcanic crisis in order to assess possible mitigation measures.

2 Measurement technique – scanning DOAS instruments

The measurement technique involves the scanning of SO_2 gas columns by collecting UV spectra. The source of radiation is scattered sunlight over 180° in a vertical plane from one horizon to the other. Each spectrum is evaluated by applying DOAS, using the zenith as a reference for the whole scan (Platt and Stutz, 2008). If the volcanic plume is located above the scanner, the vertical column density of the absorbing gases will be retrieved (Fig. 1).

The UV-spectra acquisition is made through a compacted version of the scanning NOVAC instrument (Galle et al., 2010), as shown in Fig. 2. The scanner consists of a motor-driven mirror (or prism) that directs the scattered light from the sky that has been collected through a telescope, giving a field of view (FOV) of 8 mrad. By moving the mirror, the FOV of the instrument scans a vertical plane in steps of 3.6°.

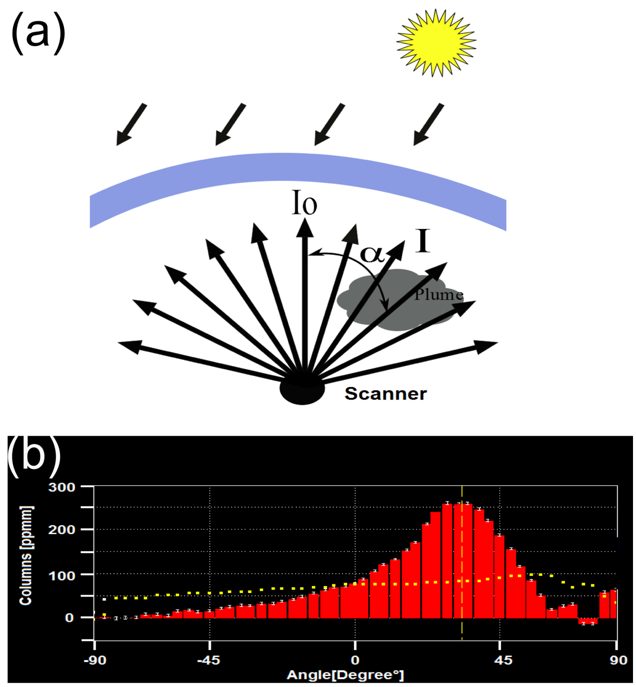

Figure 1. Scanning DOAS technique. **(a)** Scanning of scattered UV sunlight. **(b)** SO_2 columns measured from one horizon to the other. Angles with higher columns indicate the angular location of the volcanic plume.

From the telescope, light is fed by an optical fibre to a spectrometer (Ocean Optics®, S2000), which has an optical signal-to-noise ratio (SNR) of 24 dB and operates in the wavelength range 280–425 nm, divided into 2048 channels with a spectral resolution of approximately 0.6 nm. Its internal analog-to-digital converter (ADC) has a resolution of 12 bits of read-out via an RS232 interface. The rotation of the scanner, reading and storage of the spectra, and a GPS receiver are controlled by dedicated software implemented in a low-power embedded computer (MOXA® ART ARM9 RISC 192 MHz CPU with 32 MB RAM) and a 4 GB flash drive. The computer has a basic Linux distribution as the operating system, an FTP server, two Ethernet ports and two RS232 ports. After completing a scan, a compressed file (PAK format) with a size of ≈ 130 KB, containing typically 53 spectra and GPS readings, is generated and stored in the flash drive. The embedded computer and the spectrometer, which are the most fragile parts, are mounted inside a plastic Peli® enclosure with IP66 certification, thus providing protection from dust and rain.

The power consumption of the instrument, as broken down in Table 1, is approximately 9.6 W including the radio modem (see Sect. 3.2). A 60 W foldable solar panel, combined

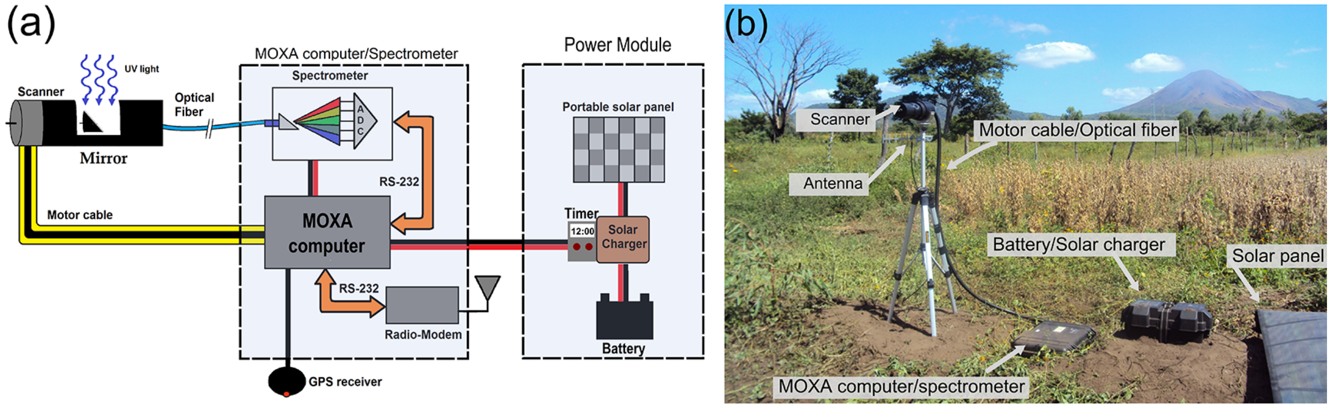

Figure 2. Compacted version of the NOVAC instrument. **(a)** Schematic of the instrument: the orange arrows are RS232 buses, the black-yellow line is the motor cable and the black-red are power lines. **(b)** Typical instrument setup. The electronic components (spectrometer, radio and embedded computer) are inside a waterproof enclosure. The scanner, the GPS and the Yagi antenna are attached to a portable aluminium tripod. The optical fibre and the motor cable are coupled to the electronic components by a plastic hose. In the background, Telica volcano.

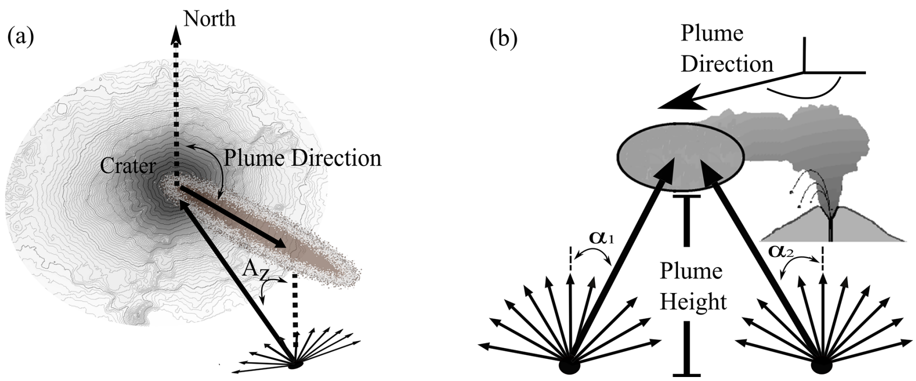

Figure 3. Geometrical parameters required for calculating SO_2 flux. **(a)** Plume direction and instrument azimuth (A_Z). **(b)** Estimation of the plume height and plume direction by simultaneous measurements using NOVAC instruments.

Table 1. Power consumption (W) of the NOVAC instrument

Component	Power consumption (W)
Scanner	3.5
Embedded computer	2.9
Spectrometer	1.9
Radio	1.3
Total	9.6

with a 12 V deep-cycle battery, provides the power supply. Since the NOVAC instrument uses sunlight as a source of radiation, the instrument is scheduled to run only during daytime using an electromechanical timer that switches the instrument on in the morning and off in the evening.

The chances of detecting and measuring a volcanic plume are determined by the meteorological conditions, particularly the wind direction. A typical installation combines two or more instruments measuring simultaneously throughout the area corresponding to the predominant wind directions.

In addition to the measurements of gas columns, the calculation of SO_2 fluxes requires updated geometrical information about the volcanic plume, as shown in Eq. (1):

$$\mathrm{Flux} = W_\mathrm{s} \cdot |\cos(P_\mathrm{d} - A_\mathrm{z})| \cdot P_\mathrm{H} \cdot \sum_{i=0}^{N-1} |\tan\alpha_{i+1} - \tan\alpha_{i-1}| \cdot \mathrm{VCD}_i . \quad (1)$$

Here, VCD_i corresponds to the SO_2 vertical column densities, estimated at the zenith angle α_i. P_d and A_z are the plume direction and the azimuth of the instrument (Fig. 3a). W_s and P_H are the plume speed and height. The plume height and direction can be calculated by combining simultaneous measurements from two NOVAC instruments (Fig. 3b). In

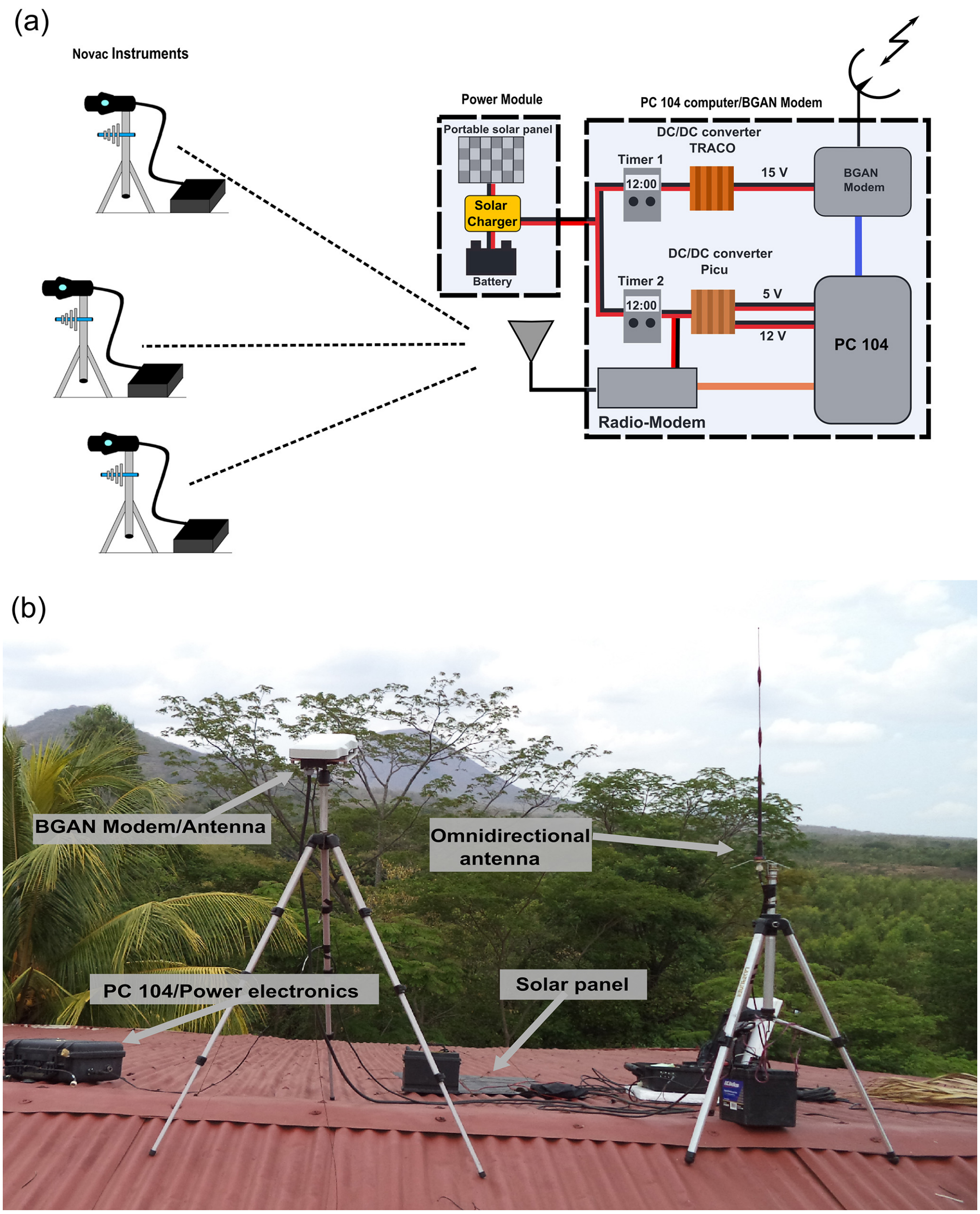

Figure 4. The RADES comprises three portable NOVAC instruments (Fig. 2) accessed by an embedded computer via a wireless link. **(a)** Schematic of the network and the PC–satellite link hub. The orange line is a RS232 bus, the blue line is Ethernet, and the black-red lines are power connections. **(b)** Instrument setup near Telica volcano (Nicaragua). The PC104 computer, the radio modem and the dc/dc converters are attached inside a waterproof enclosure.

locations with a very stable wind direction, it is possible to retrieve wind (i.e. plume) speed by using the double-beam DOAS technique (Johansson et al., 2009). However, very few locations have such stable meteorological conditions; thus, the wind speed is typically obtained from wind speed models, such as the Global Forecast System from the National Oceanic and Atmospheric Administration (NOAA).

3 Network operation and communication

System operation and satellite transfer are centralized and controlled by a PC–satellite modem hub (Fig. 4), which downloads and processes the raw measurement files (PAK format) from the NOVAC instruments through a local wireless network. The electronics of this hub are housed in a

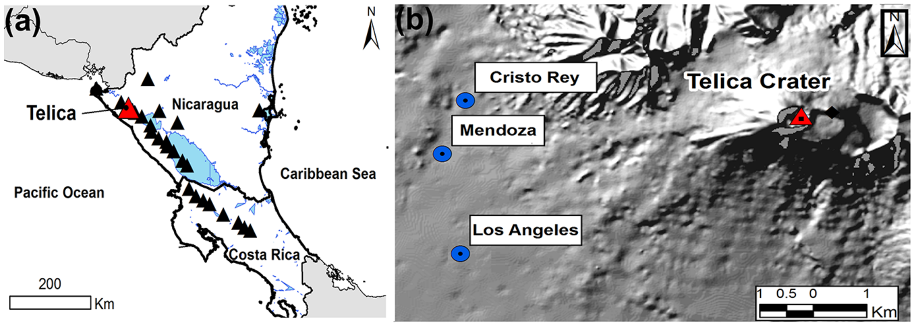

Figure 5. Field installation of the RADES around Telica volcano. **(a)** Location of Telica in Nicaragua. **(b)** Map showing the installation sites of the NOVAC instruments.

plastic Peli® enclosure that needs to be placed in a location alongside and higher than the NOVAC instruments in order to establish a reliable wireless link. Afterwards, the evaluated files are transferred to a remote server by a satellite link.

Although alternatives to satellite links are available worldwide, e.g. mobile broadband, even the most developed countries have remote areas that are not covered by these substitutes. In addition, during periods of crisis, most commercial communications systems tend to crash due to the unusually high volume of data traffic, while satellite links operate independently of local communication services (Tárraga et al., 2001).

3.1 Control system

The downloading of PAK files from the NOVAC instruments is controlled by a PC104 single-board embedded computer (PCMB-6684 manufactured by NORCO®). The computer has a fanless processor (AMD LX, 800–600 MHz), two RS232, two Ethernet ports, and a 4 GB Compact Flash storage/hard drive, and operates in the range of 0–60 °C. The operating system is Windows 2000 and the PAK files are processed using the DOAS routines implemented in the NOVAC software (Johansson, 2009). The outcome of the processed PAK file is a text file that is smaller (2 KB) but contains all the relevant information for SO_2 flux calculations, i.e. the values of the gas columns at different angles and the GPS readings.

3.2 Telemetry

The local wireless network is configured in a master–slave topology by using spread spectrum radio modems operating at a frequency of 900 MHz. The hub has a 5 dB omnidirectional antenna, while each NOVAC instrument has a 12 dB Yagi antenna. For distances of 1–3 km, these radio-frequency parameters allow typical obstacles such as vegetation or small buildings to be skipped, thus reducing the time normally required for setting and aligning a wireless network. In some circumstances, local radio regulations might not allow the use of a 900 MHz frequency, in which case models of the same type of radio operating at 2.4 GHz can be an alternative. However, higher frequencies impose stricter conditions on antenna alignments, even for short distances.

3.3 Satellite link

The satellite link is provided by a portable Inmarsat-BGAN modem that allows the evaluated files to be transferred by FTP. Processing files prior to sending them by a satellite link reduces the cost of the data transfer service, which is billed in proportion to the number of megabytes transmitted. A satellite transfer of evaluated text files ($\sim$ 2 KB apiece) costs only 3 % of the amount compared to PAK ($\sim$ 130 KB) files. The transfer cost is further optimized by scheduling the FTP transfer twice a day and combining a Python script and an electromechanical timer. This schedule, which can be easily modified if needed, ensures that every time a FTP connection is established, a certain number of files are ready to be sent, thus avoiding costly “keepalive” data packets.

3.4 Power consumption

Most of the time, when the only active devices are the PC104 computer and the radio, the PC–satellite modem hub has a power consumption of 7.3 W. During the brief periods when the satellite modem is active, the power consumption rises to around 30 W (Table 2); thus, a 60 W portable solar panel fulfils the power demand. The voltage stability requirements of the PC104 and the satellite modem are provided by two DC/DC converters that have $\approx$ 80 % efficiency.

4 Field implementation – Telica volcano

Telica is an active volcano, classified as a stratovolcano, located in the west of Nicaragua (12.602° N, 86.845° W) near the city of León (Fig. 5). The crater has an altitude of 1061 m a.s.l. and a diameter of 700 m (Smithsonian Institution, http://www.volcano.si.edu/volcano.cfm?vn=344020). It shows a well-defined volcanic plume and eruptive events that normally take place within a period of 3–5 years (Rodgers

Table 2. Power consumption (W) of the PC–satellite modem hub

Component	Power consumption (W)
Embedded computer PC104	6
Radio	1.3
Satellite modem	22
Total power (active satellite link)	29.3
Total power (idle satellite link)	7.3

et al., 2013). Due to its accessibility and good weather conditions during the dry season (November–April), this area is an excellent test site for our measurement network. Telica's volcanic activity is constantly monitored by Instituto Nicaragüense de Estudios Territoriales (INETER) through seismic stations, cameras and discrete temperature measurements. Despite the fact that this is one of the most active volcanoes in Nicaragua, very few SO_2 flux measurements were made before the implementation of this network. The best-documented previous study was a measurement campaign carried out in November 2003, using Mobile-DOAS (Galle et al., 2002) that reported values between 250 and 1200 t day^{-1} (Mather et al., 2006).

The system was tested and technically adjusted during three different periods in 2010, 2011 and 2013, each with a duration of about 2 months. The initial period, when no anomalies were reported, can be considered as the baseline measurement; the second period coincided with an eruptive crisis; and the final period can be considered to be an update of the baseline. The system was deployed on the southwest area of the volcano in accordance with the predominant wind direction. The NOVAC instruments were placed on three sites – Cristo-Rey, Mendoza and Los Angeles – while the PC–satellite modem hub was placed on the Cristo-Rey site (Fig. 5b).

4.1 Baseline period

Each volcano has an individual degassing rate; therefore, observing the changes of the flux rate rather than their absolute value is more meaningful in terms of surveillance. Continuous SO_2 flux measurements were made by the RADES from 20 January to 27 March 2010 (Fig. 6a). During this period, the flux averaged 115 ± 100 t day^{-1} and there were no other indicators of anomalous volcanic activity reported by the local authorities; thus, this period can be considered as the volcano's emissions baseline, with SO_2 degassing at a quiescent rate.

4.2 The volcanic crisis of May–June 2011

From March 2011, a gradual increase in volcanic activity was reported at Telica following a series of ash

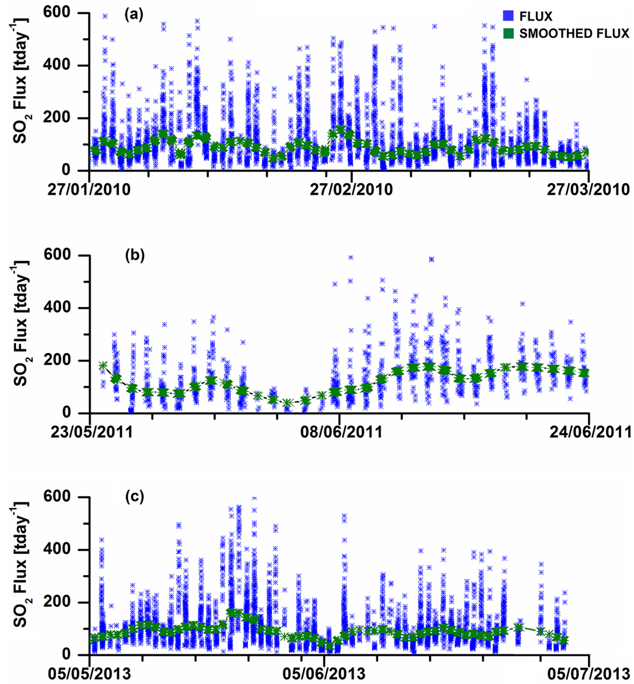

Figure 6. SO_2 emissions measured by the RADES at Telica volcano during different periods: **(a)** February–March 2010, **(b)** June 2011, **(c)** May–June 2013.

emissions and small explosions. By mid-May 2011, the rate of the explosive events was higher, leading to the evacuation of approximately 500 inhabitants from the proximity of the volcanic complex (Smithsonian Institution, http://www.volcano.si.edu/volcano.cfm?vn=344040&bgvn=1&rnum=region14&snum=nicarag&wvol=telica&tab=1). From 23 May to 24 June 2011, following a request from the local authorities, the RADES was deployed again to measure possible changes in the SO_2 emission baseline that could indicate displacements of magma to a shallower level (Fig. 6b). The previous time series of SO_2 fluxes measured in 2010 showed a pulsating signal, while during June 2011 a more sustained pattern was observed, averaging a flux rate of 140 ± 110 t day^{-1}. This minor increase of the degassing rate was not considered to be significant, and it was suggested to the local authorities that the volcanic crisis was unlikely to be linked to magmatic displacements; thus, a short-term crisis was expected. A few weeks later, on 14 June, the crisis was considered to be over, as no further explosions had been observed. A well-documented post-crisis study that included several parameters, including the SO_2 measurements made with the RADES, concluded there was no indication that the crisis was driven by magma migration and that the eruption might have been linked to the temporary sealing of the shallower hydrothermal system (Geirsson et al., 2014).

4.3 Measurements May–June 2013

After the crisis of May–June 2011, Telica has remained relatively calm and there have been no reports of significant eruptive events. As expected, the time series of SO_2 flux during May–June 2013 showed quiescent degassing with an average of $110 \pm 80\,\mathrm{t\,day^{-1}}$, which is similar to the measurements in 2010 and indicates that the flux rate has remained unchanged for the last 4 years.

5 Conclusions

This paper describes the technical aspects of designing a rapid deployment network of instruments for SO_2 flux monitoring, using compact modules that can be easily installed and transported, including a satellite data link which is completely independent of local communication services. By collecting all raw measurements in a hub, a satellite data link requires only one access point and the raw data can be processed before being transferred, thus reducing the cost of the data transfer service. The concept also allows other monitoring instruments to be added easily to the network.

The prototype was implemented and tested during three field campaigns at the Telica volcano in Nicaragua. During these campaigns, the instruments operated unattended and endured relatively high temperatures of $\approx 40\,^{\circ}\mathrm{C}$ and sporadic rainfall. The result of these measurements shows the SO_2 flux at Telica has remained relatively stable during the period 2010–2013, averaging approximately $100\,\mathrm{t\,day^{-1}}$. During the eruptive crisis of May–June 2011, despite the observed explosions and ash emissions, this average value showed little change, and thus helped to avoid false speculation and public anxiety. Telica volcano returned to its normal state after a few weeks. This average flux can be considered as a baseline of Telica volcano, which implies that SO_2 measurements reporting a flux considerably larger than $100\,\mathrm{t\,day^{-1}}$ should alert local authorities to the fact that increased surveillance efforts might be necessary. The results obtained at Telica volcano demonstrate that this system can be used to monitor unexpected eruptive crises and for studies of volcanic plumes, even for sites with limited accessibility.

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