Design of a smart and wireless seismometer for volcanology monitoring

Normandino Carreras[1*], David Mure[2], Spartacus Gomáriz[1], Daniel Mihai[1], Antoni Mànuel[1], Ramón Ortiz[3]

[1] *SARTI Research Group. Department of Electronic Engineering. Universitat Politècnica de Catalunya. Rambla de l'Exposició 24, 08800 Vilanova i la Geltrú, Spain. Email: normandino.carreras@upc.edu Tel: +34938967200*

[2] *Centro Geofísico de Canarias, Instituro Geográfico Nacional. C/ La Marina 20, 2º Santa Cruz de Tenerife, 38001 Canary Islands, Spain.*

[3] *Institute IGEO, CSIC-UCM. J. Gutierrez Abascal, 2, Madrid, 28006, Spain*

In this paper we present low-power seismic acquisition equipment for long-range telemetry, developed as a compact system for easy transportation. This acquisition system has been developed to detect the seismic activity of volcanoes, and represents the achievement of joint work from different scientific and technological disciplines such as geophysics, electronics, communications, mechanics, and information technology. The paper includes the laboratory validation results by means of automated measuring systems and calibration procedures, and the final validation results of different measurement campaigns on the *El Hierro* and Tenerife islands (Canary Islands). The seismic acquisition equipment includes an on board signal processing system developed to reduce the size of seismic data transmitted and to increase the autonomy of the equipment. Moreover, the seismic acquisition equipment has been designed based on a low cost electromagnetic sensor, which has been conditioned to achieve our goals. In a volcanic seismic survey, a series of seismic acquisition systems are placed near the area under study, where they record the natural seismic activity of volcanoes.

Keywords: volcanic monitoring, seismic acquisition, analogue to digital conversion, event detection, geophone

Highlights:

- The designed acquisition system allows the monitoring of volcanic seismic signals.
- The system consists of a custom electronic board, batteries and seismic sensors.
- Recorded data are stored in a SD memory and are sent with a radio frequency module.
- SM6 sensor is conditioned as broadband seismic sensor with electronic components.
- A field test with the designed equipment has been carried out in a volcanic zone.

1. Introduction

Earthquakes, tsunamis and volcanic eruptions are manifestations of the Earth’s energy which are important natural risk factors that can have a strong impact on the population and infrastructure in the short term. Although these phenomena are inevitable, the study of the physics of the Earth together with the continuous technological evolution, have managed to improve prediction and to respond appropriately so as to minimize their effects [1].

Seismic surveys study the propagation of elastic waves in the Earth's crust and, depending on their natural or human origin, are divided into two large families [2]. Earthquakes and the activity that occurs on the Earth’s surface such as: the activity of living beings, the interaction of air, sea, wind, vegetation, etc. [2].

In the twentieth century, the study of the propagation of seismic waves has been used to create industrial applications that today are known as applied seismic or seismic prospecting. These techniques, also known as active seismic, study the underground tomography from the analysis of the propagation of artificially produced seismic waves into the field [3]. The other technique used to obtain information about underground activity, called passive seismic, uses seismic noise data produced by the Earth's movements [4].

Currently, the study of global seismic activity is carried out through numerous observatories operated by different civil protection institutions, with an array of instrumentation mostly located at the edges of tectonic plates, where major earthquakes occur. The advances in communication technologies is providing us with real time sharing of seismic data of these seismic stations and constitutes a global network. However, because volcanos may be inactive for thousands of years, the study of volcanic seismicity is less widespread than tectonic plate seismicity. In these cases it is very difficult to justify an investment in permanent monitoring systems. However, the problem appears at the moment when the volcanoes become active, producing associated earthquakes followed by volcanic eruptions that can become catastrophic.

Commercially, there are a wide variety of seismic acquisition equipment, both for land and underwater application [6] [7]. In particular, most of these seismic systems used in volcanic monitoring are developed with broadband sensors, which are expensive and bulky, are difficult to install, and require considerable power. It is the case of Refraction Technology company inc. [6] that provides a system with a 375 mW of power consumption, but it is penalized by a reduced autonomy. Another case is Sercel [31], that has wireless communication and inside battery, but it has 130 hours of autonomy and a large infrastructure for sending data. The Spidernano of Worldsensing [29] is another system with around 500 mW and broadband sensors (with range of frequencies under 1 Hz), but it only works for 5 days.

Therefore, the most reasonable solution is to deploy a minimum amount of seismic acquisition equipment (a single seismometer if possible) in the volcanic area and then deploy a denser network of seismic acquisition equipment whenever there are changes in the level of seismic activity. As the changes in volcanic activity are increasing significantly, a greater number of measuring instruments must be deployed to be able to obtain any increase in activity [5]. These instruments tend to be inexpensive, since they function for some time until they are destroyed or deplete their energy sources. Therefore, it is necessary to have this kind of tools to respond to potential-volcanic eruptions or earthquakes without major investment of resources in instrumentation and maintenance, such as obsolete technology because of inactivity.

Before purchasing and deploying seismic acquisition equipment to record volcanic seismic activity it should be considered if the resolution is adequate to detect small changes associated with volcanic activity in its intended location. In addition, the network must be redundant to minimize the potential problems of malfunction or vandalism. In developed countries, volcanic areas are often considered as protected areas or national parks. In general, these areas are regulated by heavy environmental protection, so any type of action is very limited. Therefore, the only current solution, since environmental regulations do not allow the construction of adequate protection, is to use instruments that mimic the landscape. Hence, these restrictions do not allow the deployment of large power supply infrastructures such as solar panels to provide enough power for the seismic acquisition equipment. Moreover, the deployments of autonomous systems powered by batteries have a very limited time of operation, which is conditioned by the wireless data transmission.

Nowadays, wireless sensor networks (WSN) offer us the possibility to monitor the volcanoes seismic activity both in spatial and temporal scales. The works described in [8] and [9] presents volcanic monitoring systems based on sensor network, however both at a prototype level. The systems described in these papers are built from off the shelf modules, which are not designed to operate with low power supplies. However, these seismic acquisition equipment includes processing algorithms such as the STA/LTA (Short Term Average/Long Term Average) [26] [27], capable of performing onboard data processing and transmitting data only in the instants at which the seismic events are produced, so reducing the energy consumption of the communication system. But this seismic acquisition equipment requires a heavy (approx. 80kg), large sized base station. Also, some works of seismic networks in volcanic monitoring can be found, such as the system designed by a group of researchers from Harvard, New Hampshire and North Carolina [30]. The paper of this group presents some systems that send data to a central node which processes all data. But again it has a low autonomy of about one week and it can transmit data up to 400 meters.

This paper presents a prototype of seismic acquisition equipment for volcanic monitoring with a very low environmental impact. The equipment is a low cost, compact, lightweight, easy to install and low powered consumption system. This will represent a significant advance over existing devices, by reducing the maintenance costs and the autonomy obtained with it. It also facilitates rapid deployment without the need of high investment. This seismic acquisition equipment allows the integration of other sensors typically used in volcano monitoring, such as CO2, temperature [10], pH, deformation [11], etc. Thereby, it obtains multiparameter low cost equipment.

2. Design and specifications of the seismic acquisition equipment for volcanic monitoring

To complement the seismic networks for monitoring volcanic activity, this paper presents seismic acquisition equipment with the following specifications:

- Very low power consumption, to operate autonomously for several months (up to six months) with a minimum battery system
- Low environmental impact to operate in protected areas. No need to use solar panel or other external sources of renewable energy with a high ambient impact. Therefore, the system can operate a few centimetres below the surface to avoid visual impact and vandalism.
- Low weight, including the power supply required, which can be transported in a backpack for several hours in difficult terrain, inaccessibility and altitude.
- High degree of waterproofing, to withstand a prolonged immersion of at least one meter of water.
- On board data registry based on SD type memory, short-range telemetry (2 km) and/or both modes simultaneously.
- Price of the equipment in its standard configuration is below 1000 euros.

The components of the seismic acquisition equipment are divided into 4 modules: power supply module, control and management unit, communication peripherals and sensors. The modular design of the equipment allows more flexibility for future modifications (Figure 1).

To meet the above environmental specifications, the entire system has been mounted in a waterproof box IP67 with interior dimensions of 23.5 x 18.1 x 10.5 cm. The box has four external connections for GPS (Global Positioning System) antenna, RF antenna, a 7-pin connector for external sensors, and 4-pin connector for external power supply (Figure 2).

The components used in the design of the seismic acquisition equipment have been chosen with the main requirement to have very low power consumption. Therefore, the components were selected with the following characteristics:

- Acquisition sampling rate of 50 or 100 samples per second
- Analog to digital converter of 16 or 24 bits
- Microprocessor with main frequency of minimum 1MHz
- Microprocessor with architecture of minimum 16 bits
- UART (Universal Asynchronous Receiver Transmitter) port (minimum 2)
- SPI (Serial Peripheral Interface) port (minimum 1)
- GPIO (General Purpose digital Input/Output) programmable ports
- DMA (Direct Memory Access)
- RTC (Real Time Clock)
- Very low power
- Low cost

To select the microprocessor for the management and control unit, a benchmark of different commercial integrated microprocessors has been performed: MCF54455 Freescale [12], LM3S8962 [13], and MSP430F5438A from Texas Instruments, PIC24FJ64GB002 from Microchip. Table 1 shows the characteristics of clock speed, architecture, number of ports, consumption and prices of each microprocessor.

This study shows that those which best meet the design specifications, in terms of low-power, clock speed, number of pins, and price, are the MSP430F5438A [14] and PIC24FJ64GB002 [15]. Finally, the MSP430F5438A microprocessor has been chosen, because it has the lowest power consumption and a greater possibility of expansion ports.

The communication of Microprocessor with the RF module, the user, and the GPS system is performed through three serial ports. The communication with the SD card memory is performed through a dedicated SPI port and three other SPI ports are used for communication with three analogue to digital converters (ADC). Although the microprocessor has an integrated ADC of 12 bits, in order to obtain the desired minimum resolution, three ADCs model ADS1246 [16] from Texas Instruments have been incorporated into the design. These ADCs are 24-bit with a 3rd order modulator Delta-Sigma type with very low power consumption (2.3 mW). In Figure 2, the control and management module is depicted.

The data acquired by the ADC's can be stored on an SD memory and/or sent remotely through the RF module. For data storage an SD card memory up to 32 GB and Class 4 is used. The data are stored based on file structure following the FAT (File Allocation Table) standard. Specifically, FAT32 file system is used, which has a limitation on the number of files in each parent folder. To manage the data it requires a well-defined structure that allows migration and simple comparison between different devices. For this purpose the data is stored every second in the corresponding file, and each hour a new file is created. With each data packet stored every second, an identification frame of 18 bytes is added to the packet.

However, sending data to the remote system provides more flexibility in the processing of data in real time. In recognition campaigns, the seismometers are installed and are collected after several months of continuous recording. However, for monitoring the volcanic activity, the requirements are to have data at intervals of several days and recovery situations, crisis or eruption. Hence, the data must be available in near real time with delays of several minutes.

In order to send data remotely via radio, the microprocessor can been equipped with an XBee-PRO RF Digi 868 [17] module or a Y-Lynx [18] YLX-TRM8053-500-05 module, depending on the type of network to be used. Both modules, according to the characteristics given by their manufacturers can communicate at a distance of 40 km. In the data sending process, the same methodology discussed in storage process is followed. The time synchronization of the seismic acquisition equipment is done by the microcontroller using the integrated RTC clock and a global positioning system GPS, the FGPMMOPA6H module of GlobalTop Technology [19]. This device incorporates an antenna that facilitates in-field installation. Moreover, it allows us to place an external antenna to ensure better coverage if the equipment is installed in tunnels. The access frequency of GPS can be adjusted to minimize power consumption. In turn, the equipment can send data through the RS232 protocol to other equipment in the system. Table 2 illustrates the power consumption indicated by the manufacturer of each of the selected components of the seismic acquisition system.

In order to calculate the total power consumption, the ON/OFF time of each component of the seismic acquisition system operating in normal mode has been considered. In the case of microprocessor and A/D converter, it is estimated that it will operate 100% of the day. The GPS unit on the other hand will be connected 20 minutes per day. As for the communication module, it has established an ON time of 53%, running at 19200 bps, and transmitting 100 samples per second of the three channels with a resolution of 24 bits and an informative header. Therefore, the resulting power consumption of the seismic acquisition system is 1107.25 mW.

3. Power supply of seismic acquisition system

The power system incorporated consists of a battery and a static DC/DC converter that regulates the input voltage. Batteries must be located inside the waterproof case (Figure 3) in order to have a compact system and to facilitate transportation.

The power supply module is designed with a static DC/DC to transform and regulate the battery voltage of 3.7 V to different system voltages. In nominal operations, the seismic acquisition equipment requires ±2.5 V analogue supply for the analogue to digital converter, and two sources of +3.3 V for overall system power and for the communication module. The module designed and built, is composed of four independent DC/DC converters, which generate the voltages explained above. The input voltage of the system may be between 2.7 V and 11.5 V.

Batteries selected for this system are of Li-ion technology and provide maximum 104 Ah, offering 384.8 Wh at the nominal voltage of 3.7 V power and weigh 1.87 kg. Therefore the weight of the entire seismic acquisition equipment is only 3.7 kg. Moreover, the distribution inside the waterproof box enables doubling the number of battery units that increases the total power to 769.6 Wh and the total weight of the seismic acquisition equipment to 5.57 kg. The power module has an external connector to incorporate an AC/DC converter to recharge the batteries, to provide direct external power, or to externally place any autonomous power system if necessary.

Finally, experimental tests have been done to calculate the actual power consumption of the equipment. With the configuration given in the previous section, acquiring 3 channels at 100 samples per second without communication, the total power consumption is 149 mW. The total power consumption rises up to 1307 mW enabling the communication module. Table 3 shows the power consumption and the autonomy of the seismic acquisition equipment with different configurations.

One of the objectives of this work is to have an autonomous system to work for long periods without any maintenance. From the analysis of Table 3 it is observed that the communications module in transmission mode is the most critical situation in terms of energy consumption. Sending data over a distance of a few kilometres is overcome in units of watts of power consumption. In order to reduce it, an option is to send less data in each transmission, only sending the data when they are of interest. For this purpose, the implementation of a pre-processing on the computer itself is proposed, providing it with greater autonomy and reporting in real-time the events that occur. To achieve this purpose, from acquired data, the system could first carry out a preliminary study to determine whether an event has occurred and secondly, whether it is a volcanic event.

To incorporate algorithms that allow the classification of detected events in the recorded data and optimize the remote transmission of data into the system, a dedicated microprocessor with digital signal processing capabilities and low power consumption has been included in the design. The main microprocessor (MSP430F5438) is responsible for the control and management of seismic data, and has limited processing capabilities. Therefore a dedicated module with DSP (Digital Signal Processing) capabilities, the dsPIC33EP128GP502 from Microchip, has been selected exclusively to run the signal processing algorithms.

In dsPIC a windows algorithm, which is widely used in seismic events detection has been implemented. It is called STA/LTA [26] [27]. The verification of this event detection algorithm has been realized using signals from contrasting campaigns and with the event catalogue from the *Instituto Geográfico Nacional* in Spain. In Figure 4, an event detected on July 16, 2012 at 03:01:09 a depth of 20 km is illustrated.

4. Sensor conditioning as broadband seismic refraction sensor

In volcanic seismic monitoring, broadband sensors are normally used, as they have a wide frequency range. However, these sensors are also high cost, they require significant infrastructure for adequate installation, and often the features offered are oversized. To work on small frequency range, this type of seismic sensors requires a large mass and a large geophone. For example, the mass needed for a sensor with the natural frequency of 1 Hz compared to one of 10 Hz, supposes a modification with a scale factor of 100. It is for this reason, that geophones with a lower natural frequency have a great weight and volume, but also cost. For instance, the 3Dlite geophone from Lennartz weighs 1.6 kg and is expensive [20]. For these reasons, this type of systems will be discarded.

In this work we propose to use low cost seismic sensors such as the one used in refraction seismic, where the authors have considerable experience [28], although the frequency response has to be conditioned for its application in volcanic seismic monitoring. For this, the SM6 sensor of Input/Output [22] is used. It has a natural frequency of 4.5 Hz, 28.8 V/m/s of sensibility in open circuit, an impedance of sensor coil of 375 Ω, and 11.1 g of internal mobile mass. Each sensor is based on a moving mass inside of coil windings, being sensitive to the movement of ground vibrations. The movement of the mass inside the magnetic field generates an electrical signal proportional to the wave in the ground [21]. The sensor moves in one physical direction, therefore, in order to record in three dimensions two horizontal sensors and one vertical sensor are necessary. This seismic sensor senses the velocity and not the acceleration like in other geophones.

The volcanic seismic monitoring equipment, illustrated in Figure 2, is designed with three acquisition channels. An electromagnetic sensor is connected in each channel, allowing the acquisition of the three axes. Then, the signals recorded are processed and stored by acquisition module. Although this equipment has the inconvenience of the frequency range, it has the advantage of being small in size and is also highly sensitive. In Figure 5 the response of the SM6 sensor with natural frequency of 4.5 Hz is depicted. It is not enough for volcanic seismic monitoring, however. Therefore, to design a volcanic seismic monitoring system with this type of sensor, a conditioning circuit has been designed for SM6 sensor to move its working frequency from 4.5 Hz to 1 Hz. This circuit has been designed in two stages, filtering and amplification circuit [23]. The union of the two stages and the sensor shows a frequency response very similar to the original one form the manufacturer, but with an offset of its natural frequency.

To validate the designed conditioning circuit, preliminary simulations with PSPICE program of Cadence Design System, Inc. have been done. The electromagnetic sensor (Figure 6) equivalent circuit can be represented with passive components such as (resistors, coils, capacitors), and the vibrations generator can be represented with a source of voltage [5].

In Figure 7 the joint response of the equivalent circuit of the electromagnetic sensor and the designed conditioning circuit is presented. This graph verifies that the response of the circuit provides a natural frequency of 0.6 Hz, which is lower than the original natural frequency of 4.5 Hz of the SM6 electromagnetic sensor.

Following the simulation, laboratory tests have been carried out using a vibration system composed of the controller 455 of Beran, a power amplifier model 144 of APS Dynamics, and an actuator, the APS ELECTRO-SEIS model 129. This vibration system is designed for the calibration and testing of geophones and inertial sensors. To carry out the test, the SM6 sensor under study, the 393B31 sensor of PCB Piezotronics Inc. used as a reference, and the designed volcanic monitoring system has been installed on the vibration table (Figure 8).

The sensor response for frequency sweep from 0.5 Hz to 20 Hz applied to the SM6 sensor is illustrated in Figure 9, which are conditioned by the characteristics of the vibration table. The excitation signal amplitude peak is 500 µm for 0.5 Hz, 400 µm for frequencies between 1 Hz and 10 Hz, and 50 µm for others frequencies (10.5 Hz to 20 Hz). The sensor response for frequency sweep from 0.5 Hz to 17 Hz with an amplitude peak of 50 µm for the entire range is also illustrated. These results show that for both high and low seismic signals, the SM6 sensor responds in the same way. At the same time, the response of the electromagnetic sensor and the manufacturer's datasheet [22] (9) are compared, and it has been verified that the waveforms and the amplitudes are very similar.

Figure 10 shows the sensitivity of the SM6 sensor with the conditioning circuit in both cases. The volcanic seismic monitoring equipment is designed to acquire very small signals, but it was not possible to test these levels due to limitations of the seismic table. The results of the test show that the equipment does not work in the same way at different signal amplitudes generated by the seismic table.

In the case of small amplitudes of excitation signal, the sensor response results of the simulation (Figure 7) and of the laboratory test are similar. The low cut-off frequency appears near 1 Hz, and the high cut-off frequency appears shortly before of 10 Hz. To validate the repeatability of more than twenty tests carried out for this, the relative error between tests with the same characteristics has been calculated. The graph in Figure 11 illustrates the results obtained for the sensor under study and for the designed system. The graphic (a) shows the difference between two tests, which are representative for high amplitude ranges; and graphic (b) shows the same type of results, but for two tests which are representative for low amplitude ranges. In both graphs, it is seen that the obtained results for repeatability are very similar. At the same time, it shown that the percentage result of SM6 sensor is more stable in frequency than the same test with the complete system. This is because of the influence of the conditioning circuit in the results.

5. Experimental results

The field tests are divided into two phases, and were performed in Canary Islands. The first test field was in *La Restinga* in *El Hierro* Island (strategic area, known for the seismicity and seismic instability) [24], and the second test field was in *Las Cañadas del Teide* on *Tenerife* Island. In both field tests, the volcanic seismic acquisition system was installed to record all data in a memory card, to synchronize its internal clock with GPS every hour, but without remote data transmission. The acquisition time was relatively short, approximately one week, and it was done in a location, strongly instrumented by the IGN (*Instituto Geográfico Nacional*).

The first test field, on *El Hierro*, took place between 1 and 5 September 2014. It was installed in a building near *La Restinga*, a village. The acquisition started on the same Monday at half past seven p.m. and it ended on Friday of the same week at seven o'clock. The designed system was installed next to a Taurus seismometer from Nanometrics, in order to have a reference system to compare the results. This system had a 3Dlite sensor from Lennartz, with three channels and the natural frequency of 1 Hz. Both systems were set up to acquire with a resolution of 24 bits, 100 samples per second, and GPS synchronization.

On September 3, 2014 at 10:36 PM an event with a magnitude of 3.8º on the Richter scale was recorded, according to the event catalogue of IGN. Figure 12 (a) shows the recorded event, of volcano-tectonic type, done by the Taurus reference system indicated above, while Figure 12 (b) illustrates the same event, but in this case recorded by the designed system. If we compare the two images in Figure 12, we observe that the event recorded in (a) has a better SNR (Signal to Noise Ratio) compared to the event in (b). In this first field test, it has been verified that the system was able to record seismic signals, but it also shows that some modifications are required to reduce the SNR of the acquisition signals.

Figure 13 depicts a comparison of a random instant recording of two signals. The blue signal is the recording of the designed system, and the red signal is the recording of the reference system. In this representation, the offset of the signals is removed and these are overlapped for comparison. As seen, due to high amplitude of noise in the designed system, it was difficult to record events of very low magnitude.

Once, the seismic data was recovered and analysed, new laboratory tests have been done and the results have shown that the SNR exceed the 10000 counts of converter. After an exhaustive analysis, the origin of the noise problem was identified in the analogue to digital converter circuit, specifically in the reference voltage source (REF5020). Therefore, the negative source reference was modified and we obtained a better SNR, which changed from 10000 to only 50 counts.

The second test field done with the designed system was in a volcanic zone of *Las Cañadas del Teide* in *Tenerife* Islands [25]. For this field test, the modified system was used, and it was installed in a small house used by IGN. The reference system for this field test was a DM24 system with a CMG-6T sensor from Guralp. This system had three orthogonal channels, with 100 samples per second, and with a resolution of 24 bits. The designed system presented in this work was configured with the same parameters as the reference system. However, this reference system has installed a broadband seismic sensor with a working window up to 30 seconds and the designed system has the seismic sensor with natural frequency of 1 Hz.

Figure 14 shows the data recorded by Guralp reference system. Moreover, it must be considered that it is necessary to use filters at frequencies of interest, to better visualize the recorded signals of the broadband sensors. In the graph an event recorded around 7:33 AM near the location of field test can be observed. This was a volcano-tectonic type event with a magnitude of 1.7º on the Richter scale.

The signal of the seismic event of magnitude 1.7º on Richter scale is detailed in Figure 15. Figure (a) corresponds to the reference system with a broadband sensor and Figure (b) corresponds to the designed system. In this field test, it was verified that the designed acquisition system works properly. The system can acquire seismic signals of low magnitude, and it has achieved a noise reduction in recorded data with a better

SNR.

6. Conclusions

For this work, a new seismometer for volcanic monitoring has been designed and built, where the features of low power and weight have been studied in detail before construction. Each component has been selected after thorough comparisons of manufacturer datasheets and experimental circuits. The design of the control module of the seismic acquisition system has been done based on the very low power microprocessor, the MSP430F5438A, and the different features of the complete system have been evaluated and verified.

Moreover, a dedicated microprocessor with DSP functionalities was included in order to run real time algorithms on the system capable of identifying seismic events in the recorded data and of optimizing the remote data transmission. To this end, a window algorithm called STA/LTA (short time average/long time average), which discriminates signals against noise, whether artificial or natural origin, was included successfully in the acquisition system.

The volcanic seismic monitoring system made with SM6 sensor from Input/Output, and modified electronically as broadband sensor, was used satisfactorily in field tests in collaboration with IGN on *Tenerife* Island and *El Hierro* Island. Finally, the data obtained was compared with signals recorded by the IGN stations and the event catalogue.

This present work is a progress and an important contribution to the low cost instrumentation for volcanic monitoring activity. Since the seismic acquisition system has been designed in a modular way, it is open to the possibility to include other sensors for the volcanic monitoring such as CO2, temperature, pH, deformation, etc. hence being able to obtain a low cost, multiparameter volcanic monitoring system.

Finally, in Table 4 a summary of the main features of the designed seismic acquisition system for volcanic monitoring is detailed. And Table 5 illustrates a comparison between the equipment presented in this paper and some seismic acquisition systems discussed in this paper.

Acknowledgments

The authors would like to acknowledge the financial support of "*Ministerio de Ciencia e Innovación*" in "Interoperability and implementation of autonomous marine platforms for seismic monitoring" (INTMARSIS) CGL2013-42557-R and in "Instrumentation and Applied Technology for the Study, Characterization and Sustainable Exploration of Marine Environment" (MarInTech) CTM2015-68804-REDT

References

[1] Servando De la Cruz-Reyna, Marta Tárrega, Ramón Ortiz, Alicia Martínez-Bringas. "Tectonic earthquakes triggering volcanic seismicity and eruptions. Case studies at Tungurahua and Popocatépetl volcanoes". Journal of Volcanology and Geothermal Research 193. pp 37-48. March 2010.

[2] José M. Azañón Hernandez, Antonio Azor Pérez, Francisco M. Alonso Chaves, Miguel Orozco Fernández. "Geología Física". Ed. Paraninfo. 2002. ISBN 84-9732-021-2

[3] Robert E. Sheriff, Lloyd P. Geldart "Exploration seismology". Cambridge University Press. Second Edition 1995. ISBN 0-521-46826-4

[4] R. J. Ritta, J. C. Massa, G. D. Chiappero. "Processing of ambient vibration records for estimation of the fundamental vibration period of soil deposits". IEEE Latin America transactions, Vol. 11, nº 1, pp. 300-306, February 2013.

[5] Ramón Ortiz, Alicia García, Mar Astiz "Instrumentación en volcanología". Editor Excmo. Cabildo Insular de Lanzarote. October, 2001. ISBN 84-97021-84-0

[6] Refraction Technology, Inc. http://www.reftek.com Retrieved January 28, 2015.

[7] Guralp systems. http://www.guralp.com Retrieved January 27, 2015

[8] Wen-Zhan Song, Renjie Huang, Mingsen Xu, Behrooz A. Shirazi, Richard LaHusen. “Design and deployment of sensor network for real-time high-fidelity volcano monitoring” IEEE Transactions on parallel and distributed systems, vol.21, no.11, November 2010.

[9] G. Werner-Allen, J. Johnson, M. Ruiz, J. Lees, M. Welsh. “Monitoring volcanic eruptions with a wireless sensor network”. Proceedings of the second wireless sensor networks, pp. 108-120, January 31 – February 2, 2005.

[10] David Moure, Pedro Torres. “Low power and high efficiency energy acquisition systems for volcano monitoring” IMEKO TC-4 2013, Symposium Measurements of Electrical Quantities. 2013 July 18-19, Barcelona (Spain) ISBN 978-84-616-5438-3

[11] Tomoji Takasu, Akio Yasuda. “Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB” International Symposium on GPS/GNSS, International Convention Center Jeju, Korea. November 4-6, 2009.

[12] Microcontroller Solutions Group. “MCF54455 Reference Manual” Freescale Semiconductor. Rev. May 6, 2011

[13] “Stellaris LM3S8962 Microcontroller Data sheet SPMS001l” Texas Instruments. July 15, 2014

[14] “MSP430x5xx and MSP430x6xx Family User’s Guide SLAU208O” Texas Instruments. June 2008

[15] “Microchip PIC24FJ64GB004 Family Data sheet DS39940D” Microchip Technology. 2010. ISBN 978-1-60932-439-1

[16] “24-Bit analog-to-digital converters for temperature sensors SBAS428G” Texas Instruments. October 2011

[17] “XBee-PRO®868 RF Modules” Digi International inc. 11001 Bren Road East, Minnetonka, MN 55343. Revision 90001020_B. 24 February 2011

[18] “Data sheet YLX-TRM8053-500-05” Y-Lynx Rue Galilée 15, CH-1400 YVERDON, Switzerland. January 2011

[19] GlobalTop Technology Inc., FGPMMOPA6H GPS Standalone Module Datasheet, revision V0A. 31, January 2012

[20] Lennartz Electronic GMBH. Seismometers manufacturer. http://www.lennartz-electronic.de Retrieved September 2, 2015

[21] Jens Havskov, Gerardo Alguacil. “Instrumentation in Earthquake Seismology” series: Modern Approaches in Geophysics, Vol.22. Springer. 360 pp. 2004. ISBN 978-94-017-5113-1

[22] Sensor Nederland b.v. Geophone manufacturer of Input/Output, funded in 1968 and renamed as ION in 2007. www.iongeo.com Retrieved March16, 2015.

[23] Robert F. Coughlin, Frederick F. Driscoll. “Amplificadores operacionales y circuitos integrados lineales” 4th edition. Ed. Prentice-Hall hispanoamericana. Mexico, 1993. ISBN 968-880-284-0.

[24] C. López, M. J. Blanco, R. Abella, B. Brenes, V. M. Cabrera Rodríguez, B. Casas, I. Domínguez Cerdeña, A. Felpeto, M. Fernández de Villalta, C. del Fresno, O. García, M.J. García-Arias, L. García-Cañada, A. Gomis Moreno, E. González-Alonso, J. Guzmán Pérez, I. Iribarren, R. López-Díaz, N. Luengo-Oroz, S. Meletlidis, M. Moreno, D. Moure, J. Pereda de Pablo, C. Rodero, E. Romero, S. Sainz-Maza, M.A. Sentre Domingo, P.A. Torres, P. Trigo, V.Villasante-Marcos. “Monitoring the volcanic unrest of El Hierro (Canary Islands) before the onset of the 2011-2012 submarine eruption”. Geophysical Research Letters (An AGU journal). Volume 39. Issue 13. July 2012.

[25] I. Domínguez Cerdeña, C. del Fresno, L. Rivera. “New insight on the increasing seismicity during Tenerife’s 2004 volcanic reactivation” Journal of volcanology and geothermal research. Ed. Elsevier. Volume 206. Issues 1-2. pp. 15-29. 1 September 2011.

[26] Mitchell Withers, Richard Aster, Christopher Young, Judy Beiriger, Mark Harris, Susan Moore, and Julian Trujillo. “A comparison of select trigger algorithms for automated global seismic phase and event detection”. Bulletin of the seismological society of America, vol. 88, nº 1. Pp 95-106. February 1998

[27] B. K. Sharma, Amod Kumar, V. M. Murthy. “Evaluation of seismic events detection algorithms”. Journal geological society of India. Vol. 75, pp 533-538. March 2010.

[28] Antoni Mànuel, Xavier Roset, Joaquín Del Rio, Daniel Mihai Toma, Normandino Carreras, Shahram Shariat Panahi, Albert Garcia-Benadí, Tim Owen, Javier Cadena. “Ocean Bottom Seismometer: Design and Test of a Measurement System for Marine Seismology” Sensors 2012, pp. 3693-3719, March 2012.

[29] Worldsensing. Spidernano manufacturer designed to seismic acquisition. http://www.spidernano.com Retrieved January 28, 2015.

[30] Geoffrey Werner-Allen, Konrad Lorincz, Matt Welsh, Omar Marcillo, Jeff Johnson, Mario Ruiz, Jonathan Lees. “Deploying a wireless sensor network on an active volcano”. Internet Computing. Volume 10, Issue 2, pp 18-25. March-April 2006.

[31] Sercel. Seismic acquisition systems http://www.sercel.com/Pages/default.aspx Retrieved October 14, 2016.